CAMPG

Computer Aided Modeling Program
with Graphical Input
Version 5.5
WINDOWS XP

USER'S MANUAL

Cadsim Engineering
P.O. Box 4083 Davis, Ca 95617
http://www.bondgraph.com

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*The Universal Bond Graph Modeling Preprocessor
for Dynamic and Mechatronics Systems*

Cadsim Engineering
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http:/www.bondgraph.com

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Chapter 1

CAMPG QUICK START

1.1 INSTALLATION

Using Windows Explorer point to the directory of the CAMPG CD. Open the file listing on the CD and click on the “SetupWindows-XP.bat" file. CAMPG will install on your computer and will create a “c:\Campg Working” directory, CAMPG folder on your desktop and a CAMPG entry on your Start/Programs listing.

The CAMPG folder on your desktop and the CAMPG entry on the START/ALL Programs listing contain the following icons.

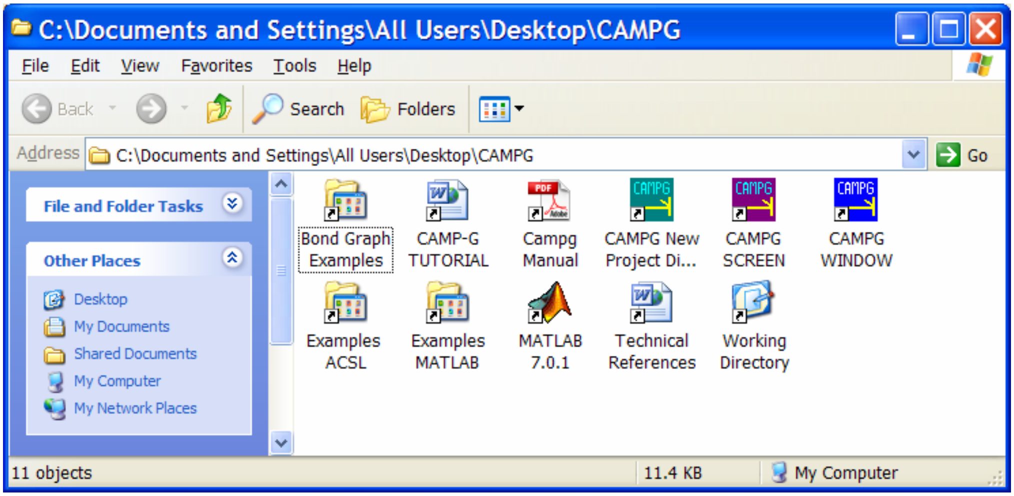


Fig. 1.1 CAMPG icons set

1.2 CAMPG ICONS SET

This icon is used to run CAMPG in full screen and also in a Window. If you double click on this icon CAMPG will start in full screen but if you enter Alt-Enter, it will run in a window.

This icon is used to run CAMPG exclusively in full screen. You may see some messages that are unique to windows XP as it checks the communication ports. Click on ignore and the program will execute normally.

CAMPG by default uses a working directory with name "c:\Campg Working" when the program is started with any of the icons above. You can use this Icon to create a different working directory for a new project. When you use this, a New Project Working directory is created under c:\Campg Working directory and also in the Desktop. This gives you the opportunity to work either on the new working directory on the desktop of the c:\Camg Working\New project directory or in the desktop. You can change the name of this directory or move it to a new location you want. To activate CAMPG with this New Working Directory, click on the session file or other .bg file in this directory and enter your new Bond Graph Model in CAMPG.

This icon is used to look at the CAMPG documentation. This manual in PDF format is available to the user. Double click on this and if you have the Adobe Acrobat reader installed on your computer you will be able to see this entire manual electronically.

CAMP-G
TUTORIAL

CAMPG has a tutorial on line also. The tutorial will appear in form of a local Web page with links to follow and point out to the different instructional presentations.

Bond Graph
Examples

This icon points to the Bond Graph Examples directory with contain a set of .bg files with are bond graph examples that can be modeled and processed for all CAMPG interfaces.

MATLAB
7.0.1

This icon links MATLAB with the c:\CAMPG WORKING directory. If you double click on this icon, the MATLAB command windows and the last CAMPG files input for MATLAB will start.

Examples
ACSL

This icon opens a directory with examples of the CAMPG-ACSL generated files.

Examples
MATLAB

This icon opens the directory with examples of the CAMPG-MATLAB generated files.

Technical
References

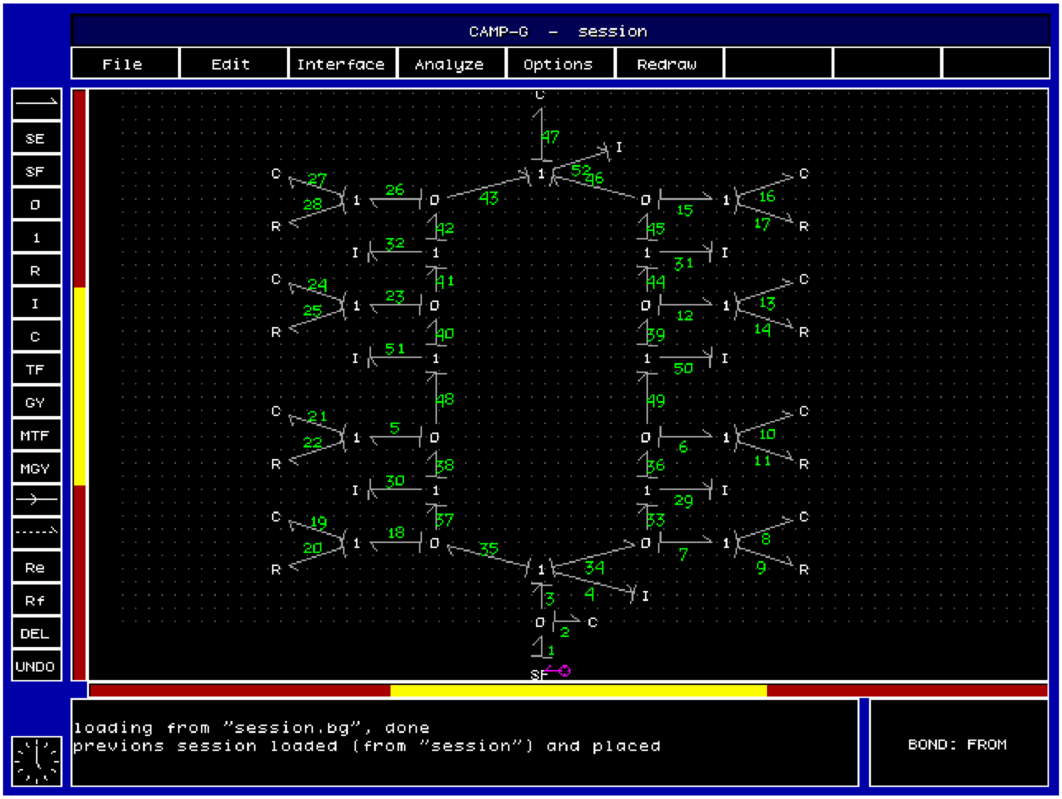
When this icon is clicked, a local web page with links to the different publications will appear.

Working
Directory

When this icon is clicked the user opens the c:\Campg Working directory.

1.7 Bond Graph Model Entry

CAMPG will start and after an initial display of the uses and license, move the mouse and the following display will appear.

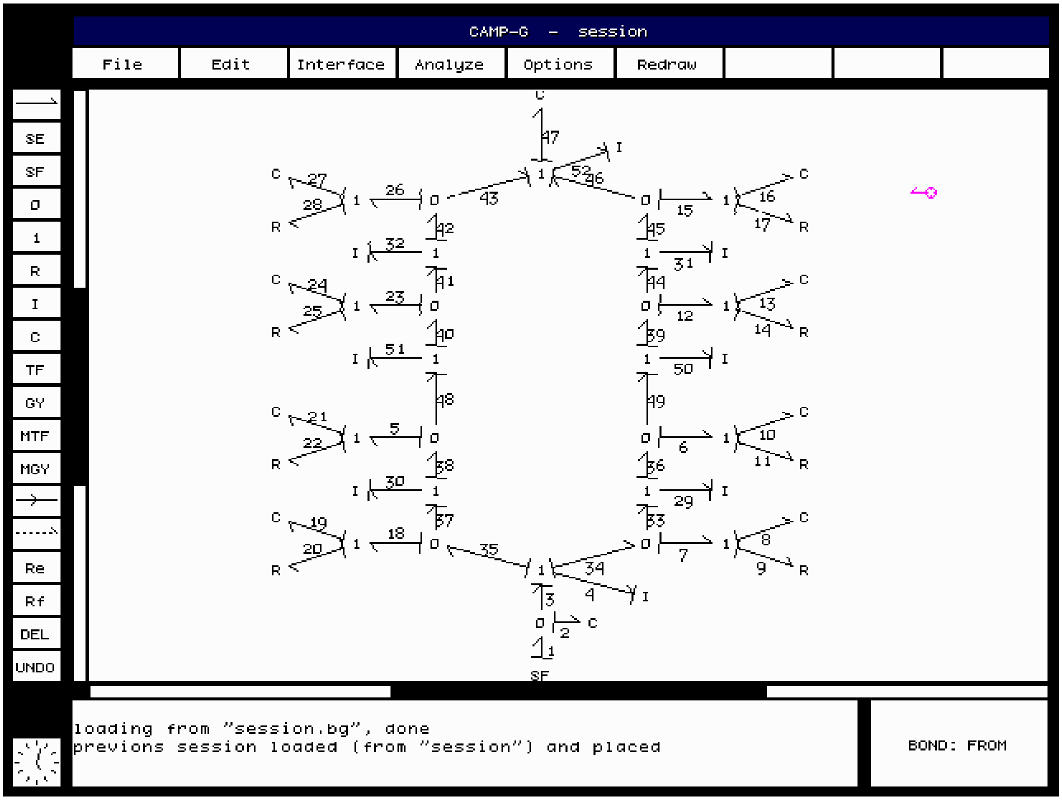


```
loading from "session.bg", done
previons session loaded (from "session") and placed
```

Fig 1.2 CAMPG initial session.bg display

The previous screen uses the default configuration setting for the screen background and colors. However the user can operate

CAMPG in black and white. The reason is that the user can take screen shots and capture the CAMPG window display and its bond graph. Back and white displays are usually preferred for documentation purposes and to enter into a word processing or presentation software like PowerPoint. The following figure illustrates this kind of display.

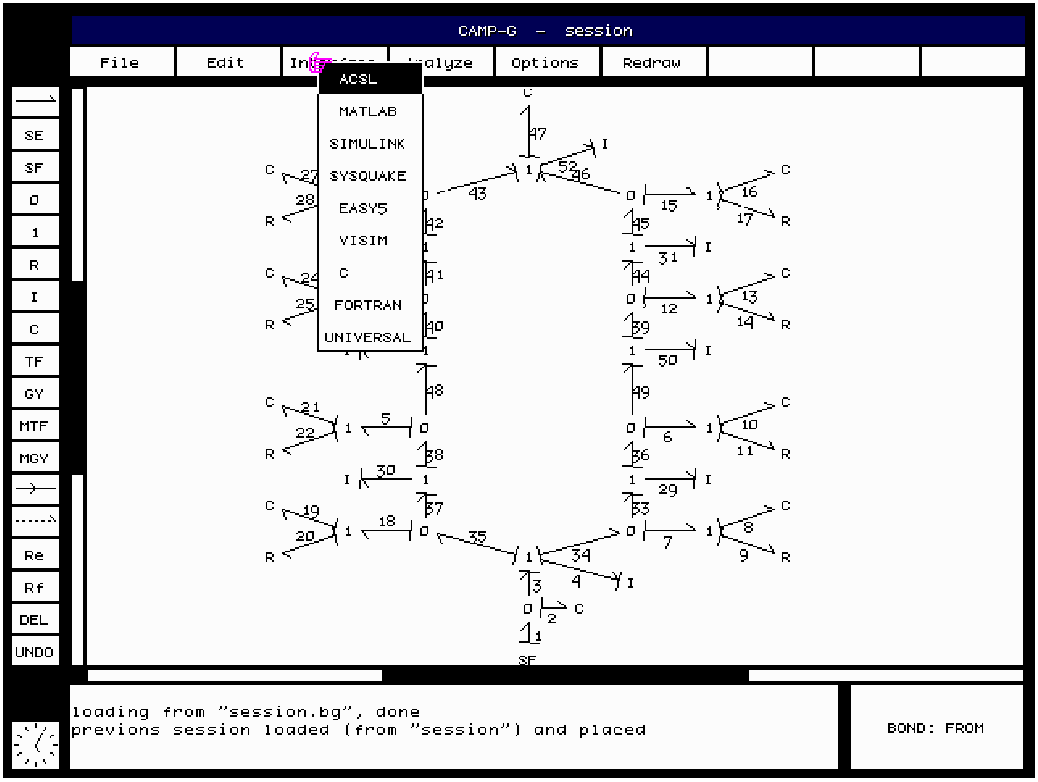


```
loading from "session.bg", done
previons session loaded (from "session") and placed
```

```
BOND: FROM
```

Fig 1.3 CAMPG black and white display. Use the OPTIONS menu to change to black and white display.

The user at this point is free to enter a new Bond Graph Model in CAMPG and have CAMPG generated the code that goes into the different simulation environments. This menu is reached by clicking on the INTERFACE menu.

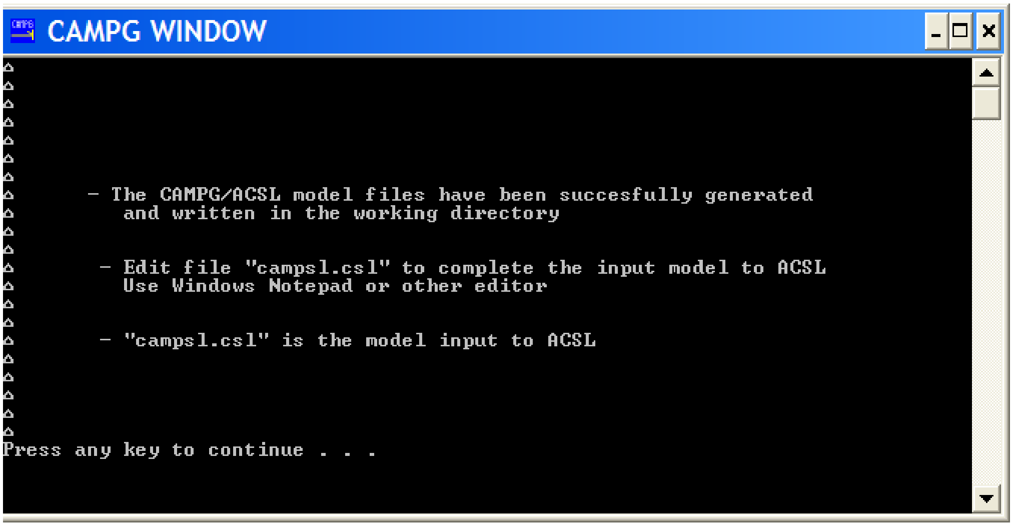


```
loading from "session.bg", done
previons session loaded (from "session") and placed
```

Fig 1.4 CAMPG INTERFACE menu

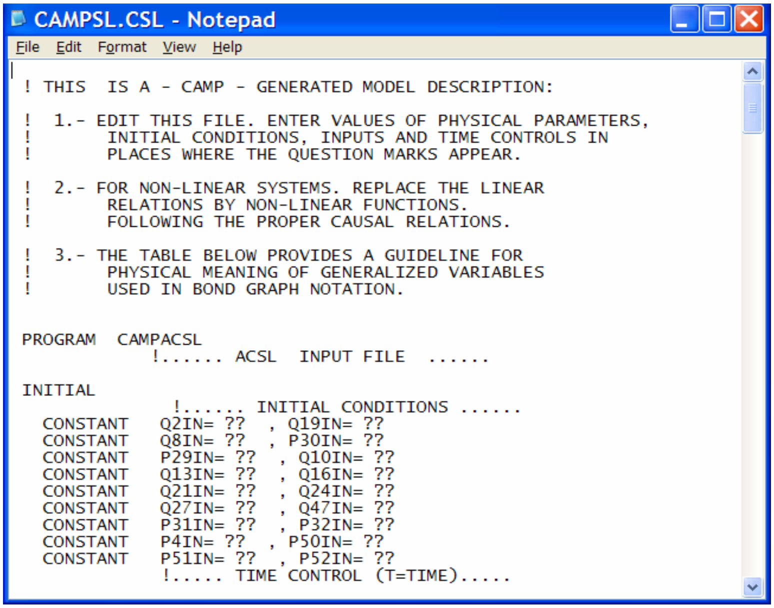
1.8   CAMPG/ ACSL INTERFACE

Once the Bond Graph model has been entered into CAMPG, it will generate the appropriate files for the interface input files to ACSL. Choose the ACSL option interface from the menu. CAMPG will interface with the user with a window that looks like the following figure.



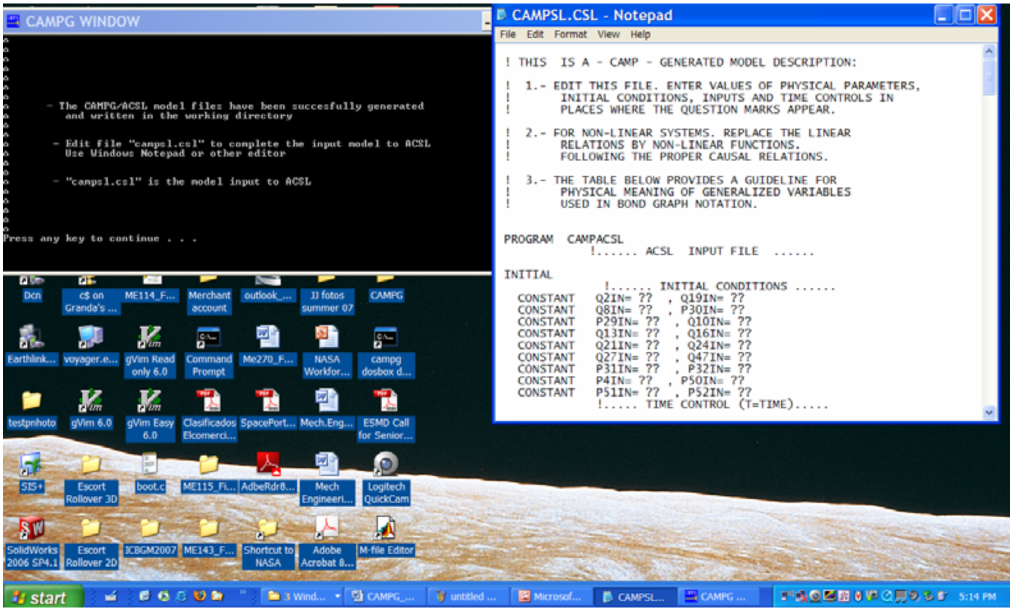
```
⌂
⌂
⌂
⌂
⌂
⌂
⌂
⌂      - The CAMPG/ACSL model files have been succesfully generated
⌂         and written in the working directory
⌂
⌂
⌂       - Edit file "campsl.csl" to complete the input model to ACSL
⌂         Use Windows Notepad or other editor
⌂
⌂
⌂       - "campsl.csl" is the model input to ACSL
⌂
⌂
⌂
⌂
⌂
Press any key to continue . . .
```

Fig 1.5   CAMPG/ACSL console window



```
 ! THIS  IS A - CAMP - GENERATED MODEL DESCRIPTION:

 !  1.- EDIT THIS FILE. ENTER VALUES OF PHYSICAL PARAMETERS,
 !       INITIAL CONDITIONS, INPUTS AND TIME CONTROLS IN
 !       PLACES WHERE THE QUESTION MARKS APPEAR.

 !  2.- FOR NON-LINEAR SYSTEMS. REPLACE THE LINEAR
 !       RELATIONS BY NON-LINEAR FUNCTIONS.
 !       FOLLOWING THE PROPER CAUSAL RELATIONS.

 !  3.- THE TABLE BELOW PROVIDES A GUIDELINE FOR
 !       PHYSICAL MEANING OF GENERALIZED VARIABLES
 !       USED IN BOND GRAPH NOTATION.


PROGRAM  CAMPACSL
            !...... ACSL  INPUT FILE  ......

INITIAL
              !...... INITIAL CONDITIONS ......
  CONSTANT   Q2IN= ??  , Q19IN= ??
  CONSTANT   Q8IN= ??  , P30IN= ??
  CONSTANT   P29IN= ??  , Q10IN= ??
  CONSTANT   Q13IN= ??  , Q16IN= ??
  CONSTANT   Q21IN= ??  , Q24IN= ??
  CONSTANT   Q27IN= ??  , Q47IN= ??
  CONSTANT   P31IN= ??  , P32IN= ??
  CONSTANT   P4IN= ??  , P50IN= ??
  CONSTANT   P51IN= ??  , P52IN= ??
             !..... TIME CONTROL (T=TIME).....
```

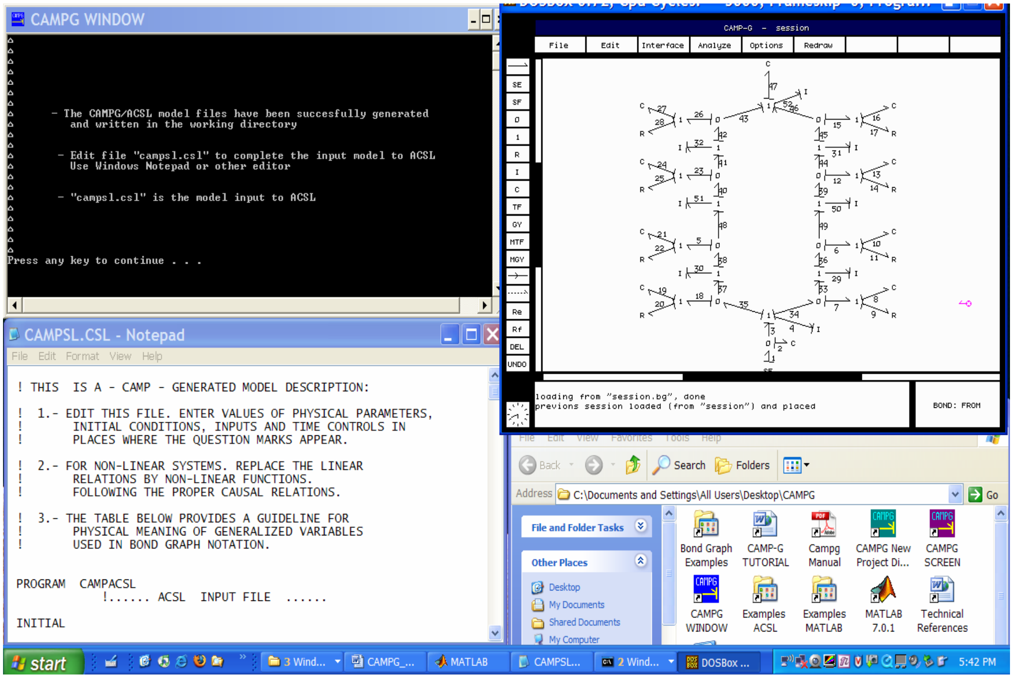
Fig 1.6 CAMPSL.CSL input files



```
   - The CAMPG/ACSL model files have been succesfully generated
     and written in the working directory

    - Edit file "campsl.csl" to complete the input model to ACSL
      Use Windows Notepad or other editor

    - "campsl.csl" is the model input to ACSL


Press any key to continue . . .
```

```
! THIS  IS A - CAMP - GENERATED MODEL DESCRIPTION:

!  1.- EDIT THIS FILE. ENTER VALUES OF PHYSICAL PARAMETERS,
!       INITIAL CONDITIONS, INPUTS AND TIME CONTROLS IN
!       PLACES WHERE THE QUESTION MARKS APPEAR.

!  2.- FOR NON-LINEAR SYSTEMS. REPLACE THE LINEAR
!       RELATIONS BY NON-LINEAR FUNCTIONS.
!       FOLLOWING THE PROPER CAUSAL RELATIONS.

!  3.- THE TABLE BELOW PROVIDES A GUIDELINE FOR
!       PHYSICAL MEANING OF GENERALIZED VARIABLES
!       USED IN BOND GRAPH NOTATION.


PROGRAM  CAMPACSL
              !...... ACSL  INPUT FILE  ......

INITIAL
                !...... INITIAL CONDITIONS ......
  CONSTANT   Q2IN= ??  , Q19IN= ??
  CONSTANT   Q8IN= ??  , P30IN= ??
  CONSTANT   P29IN= ??  , Q10IN= ??
  CONSTANT   Q13IN= ??  , Q16IN= ??
  CONSTANT   Q21IN= ??  , Q24IN= ??
  CONSTANT   Q27IN= ??  , Q47IN= ??
  CONSTANT   P31IN= ??  , P32IN= ??
  CONSTANT   P4IN= ??  , P50IN= ??
  CONSTANT   P51IN= ??  , P52IN= ??
               !..... TIME CONTROL (T=TIME).....
```

Fig 1.7 CAMPG console and ACSL input file



```
   - The CAMPG/ACSL model files have been succesfully generated
     and written in the working directory

    - Edit file "campsl.csl" to complete the input model to ACSL
      Use Windows Notepad or other editor

    - "campsl.csl" is the model input to ACSL


Press any key to continue . . .
```

```
loading from "session.bg", done
previons session loaded (from "session") and placed
```

```
! THIS  IS A - CAMP - GENERATED MODEL DESCRIPTION:

!  1.- EDIT THIS FILE. ENTER VALUES OF PHYSICAL PARAMETERS,
!       INITIAL CONDITIONS, INPUTS AND TIME CONTROLS IN
!       PLACES WHERE THE QUESTION MARKS APPEAR.

!  2.- FOR NON-LINEAR SYSTEMS. REPLACE THE LINEAR
!       RELATIONS BY NON-LINEAR FUNCTIONS.
!       FOLLOWING THE PROPER CAUSAL RELATIONS.

!  3.- THE TABLE BELOW PROVIDES A GUIDELINE FOR
!       PHYSICAL MEANING OF GENERALIZED VARIABLES
!       USED IN BOND GRAPH NOTATION.


PROGRAM  CAMPACSL
              !...... ACSL  INPUT FILE  ......

INITIAL
```

Fig 1.8   CAMPG/ACSL working display including the Bond Graph model

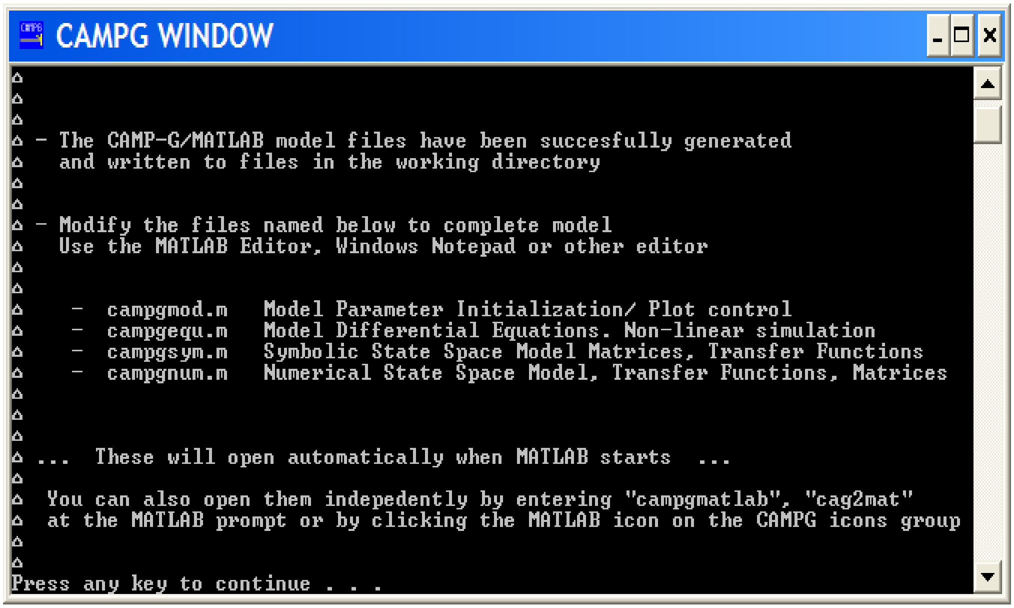
Window.

The user can utilize several display options to work with CAMPG/ACSL It is suggested the user work with a set of windows that contain the CAMPG console window and the ACSL input files. Such displays can look like the figures above.

1.9 CAMPG/MATLAB Interface

The CAMPG/MATLAB interface works with a graphics window and a console window. When CAMPG is started with the CAMPG Screen icon then the console and the Graphics window are superimposed on one another and only appear in sequence.

The console window is used to give messages to the user after CAMPG has started the prepossessing of input files to MATLAB. The console for CAMPG/MATLAB will look like the following figure.



```
⌂
⌂
⌂
⌂ - The CAMP-G/MATLAB model files have been succesfully generated
⌂   and written to files in the working directory
⌂
⌂
⌂ - Modify the files named below to complete model
⌂   Use the MATLAB Editor, Windows Notepad or other editor
⌂
⌂
⌂    -  campgmod.m   Model Parameter Initialization/ Plot control
⌂    -  campgequ.m   Model Differential Equations. Non-linear simulation
⌂    -  campgsym.m   Symbolic State Space Model Matrices, Transfer Functions
⌂    -  campgnum.m   Numerical State Space Model, Transfer Functions, Matrices
⌂
⌂
⌂
⌂ ...  These will open automatically when MATLAB starts  ...
⌂
⌂  You can also open them indepedently by entering "campgmatlab", "cag2mat"
⌂  at the MATLAB prompt or by clicking the MATLAB icon on the CAMPG icons group
⌂
⌂
Press any key to continue . . .
```

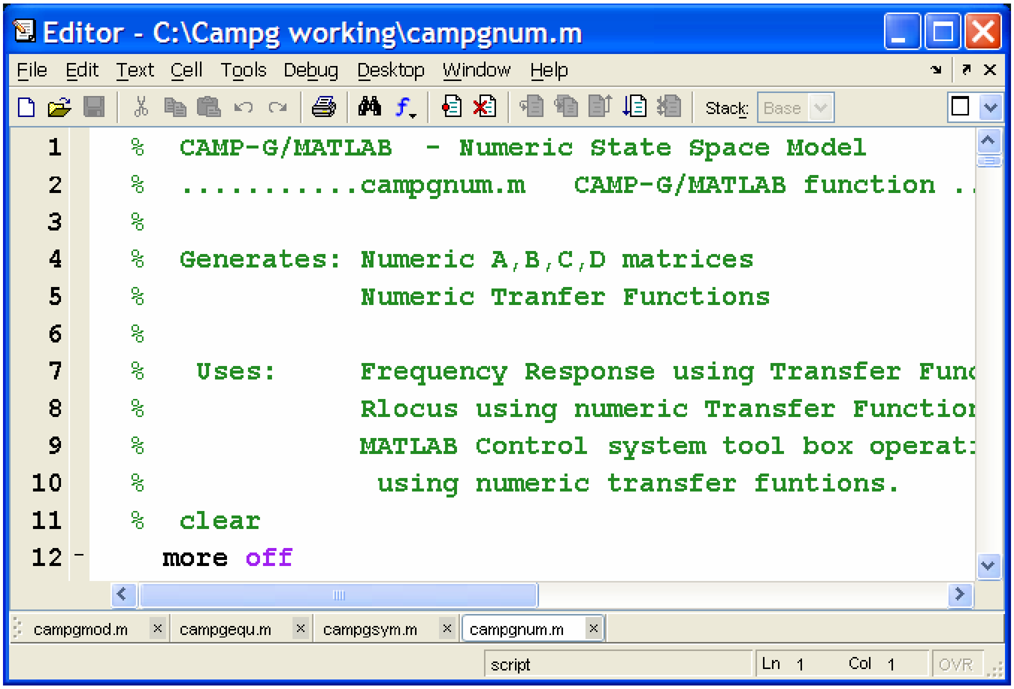
Fig 1.9. CAMPG/MATLAB message console display

CAMPG/MATLAB will automatically interface to MATLAB and will open the MATLAB command console ant the MATLAB input files in the form of .m files input to MATLAB. These four files are displayed in a window with tabs.

The files generated will be:

- campgmod.m   Model Parameter Initialization/ Plot control
- campgequ.m   Model Differential Equations. Non-linear simulation
- Campgsym.m   Symbolic State Space Model Matrices, Transfer Functions
- Campgnum.m   Numerical State Space Model, Transfer Functions, Matrices

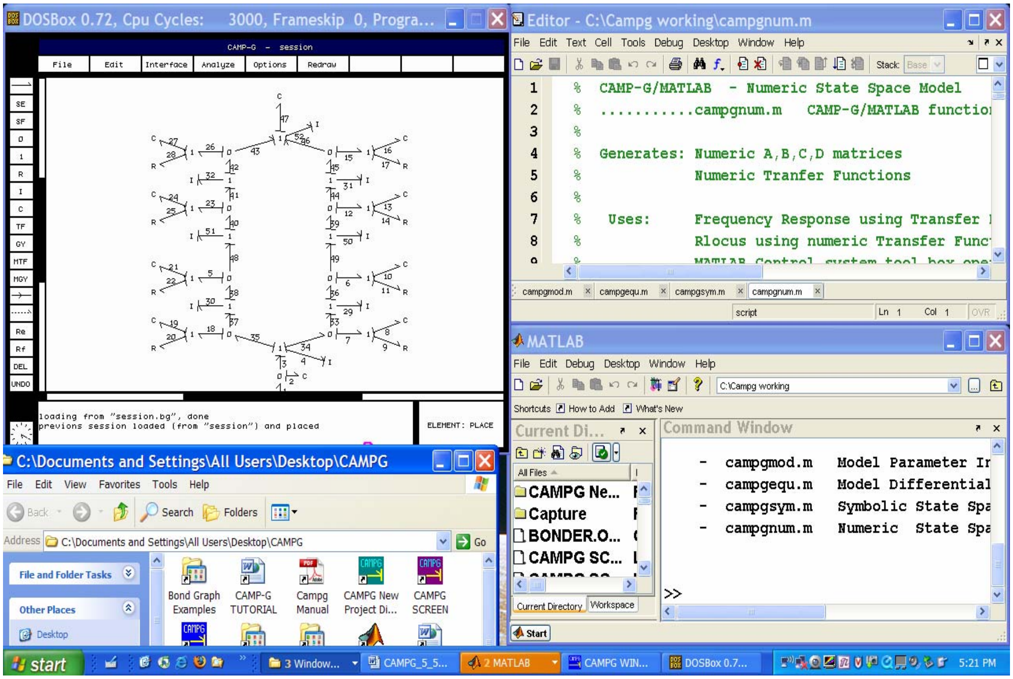
These will open automatically when MATLAB starts   The user can also open them independently by entering "campgmatlab" or "cag2mat" at the MATLAB prompt or by clicking the MATLAB icon on the CAMPG icons group The display will look like illustrated in the figure below.



```
  %  CAMP-G/MATLAB  - Numeric State Space Model
  %  ...........campgnum.m   CAMP-G/MATLAB function ..
  %
  %  Generates: Numeric A,B,C,D matrices
  %             Numeric Tranfer Functions
  %
  %   Uses:     Frequency Response using Transfer Func
  %             Rlocus using numeric Transfer Functior
  %             MATLAB Control system tool box operat:
  %              using numeric transfer funtions.
  %  clear
- more off
```

Fig 1-10 CAMPG/MATLAB input files display

Yet there is another option. The bond graph can be displayed using the CAMPG window display and entering a command to rearrange the windows horizontally or vertically we have the following display.



```
loading from "session.bg", done
previons session loaded (from "session") and placed
```

```
%   CAMP-G/MATLAB  - Numeric State Space Model
%   ...........campgnum.m   CAMP-G/MATLAB functio
%
%   Generates: Numeric A,B,C,D matrices
%              Numeric Tranfer Functions
%
%    Uses:     Frequency Response using Transfer
%              Rlocus using numeric Transfer Func
%              MATLAB Control system tool box ope
```

```
     -  campgmod.m   Model Parameter Ir
     -  campgequ.m   Model Differential
     -  campgsym.m   Symbolic State Spa
     -  campgnum.m   Numeric  State Spa

>>
```

Fig 1-11 CAMPG/MATLAB interface with Bond Graph Window

1.10 The CAMPG/SIMULINK interface

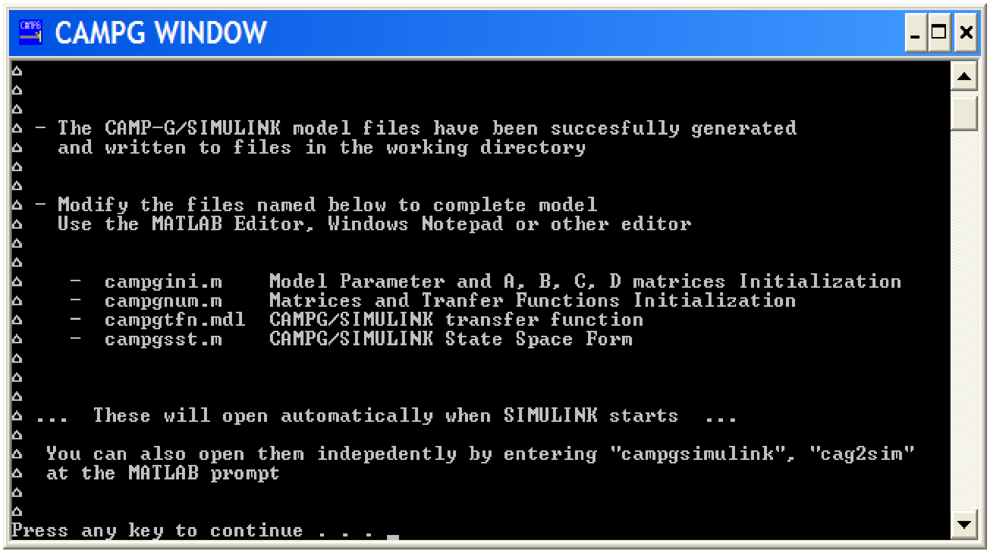
CAMPG interface to SIMULINK follows the same format as the one for MATLAB. The user enters a Bond Graph model utilizing the mention of the left and at the top and then chooses the SIMULINK interface under the INTERFACE menu

The following files will be generated.

- campgini.m Model Parameter and A, B, C, D matrices Initialization
- campgnum.m Matrices and Transfer Functions Initialization
- campgtfn.mdl CAMPG/SIMULINK transfer function
- campgsst.m CAMPG/SIMULINK State Space Form

... These will open automatically when SIMULINK starts ...

The user can also open them independently by entering "campgsimulink", "cag2sim" at the MATLAB prompt



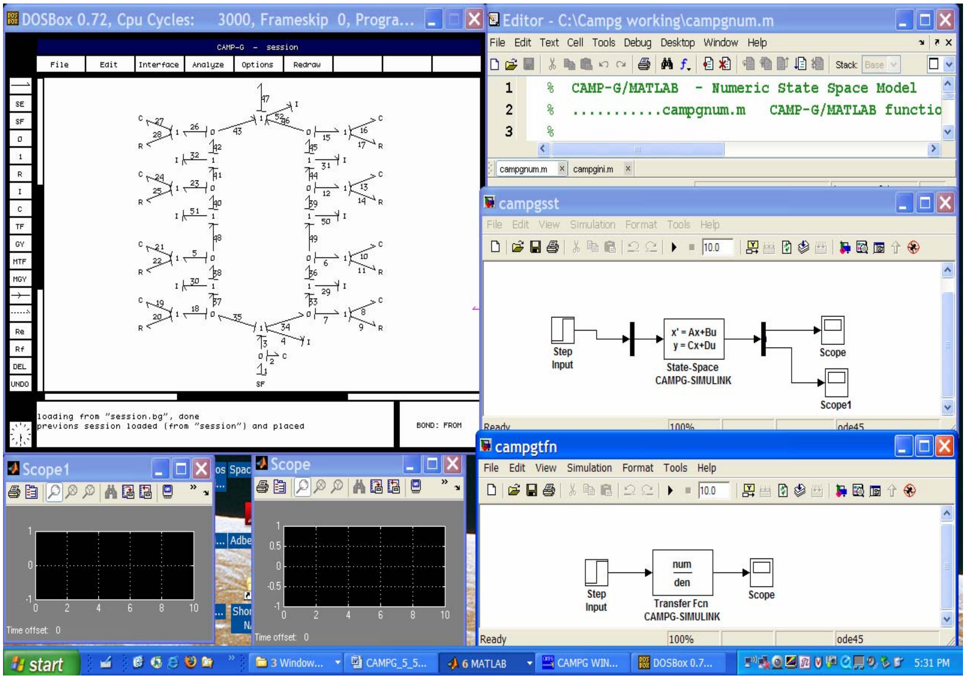
```
⌂
⌂
⌂
⌂ - The CAMP-G/SIMULINK model files have been succesfully generated
⌂   and written to files in the working directory
⌂
⌂
⌂ - Modify the files named below to complete model
⌂   Use the MATLAB Editor, Windows Notepad or other editor
⌂
⌂
⌂    -  campgini.m    Model Parameter and A, B, C, D matrices Initialization
⌂    -  campgnum.m    Matrices and Tranfer Functions Initialization
⌂    -  campgtfn.mdl  CAMPG/SIMULINK transfer function
⌂    -  campgsst.m    CAMPG/SIMULINK State Space Form
⌂
⌂
⌂
⌂ ...   These will open automatically when SIMULINK starts   ...
⌂
⌂  You can also open them indepedently by entering "campgsimulink", "cag2sim"
⌂  at the MATLAB prompt
⌂
⌂
Press any key to continue . . .
```

Fig 1.12 CAMPG/SIMULINK Console and messages display.

These files describe the model for SIMULINK. Since SIMULINK and MATLAB share the same working space, the initialization parameters in the CAMPGINI. M file initialize not only the physical parameters for simulation but also CAMPG has set up the initialization of the system A, B, C, D matrices. Keep in mind that these are generated in symbolic form and can be used that way to program hardware in the loop. These are initialized in the work space and their values are transferred to the SIMULINK state space blocks. The

CAMPGNUM.M generated the transfer functions which are also initialized on the SIMULINK transfer function block.

The model transferred from CAMPG to SIMULINK in the state space form, follows the same order of the state space vector as the state variable vector generated in CAMPG and displayed in the CAMPGINI.M file and in the CAMPGNUM.m file. The rows of those matrices correspond to the rows of the state variable vector generated in those two files. The State Space Model in SIMULINK requires two additional blocks, Multiplexer for the input vector and a Demultiplexer for the vector of outputs. Both of these are already included in the .mdl files that open as the CAMPG/SIMULINK interface executes.



```
% CAMP-G/MATLAB  - Numeric State Space Model
% ...........campgnum.m   CAMP-G/MATLAB functio
%
```

```
loading from "session.bg", done
previons session loaded (from "session") and placed
```

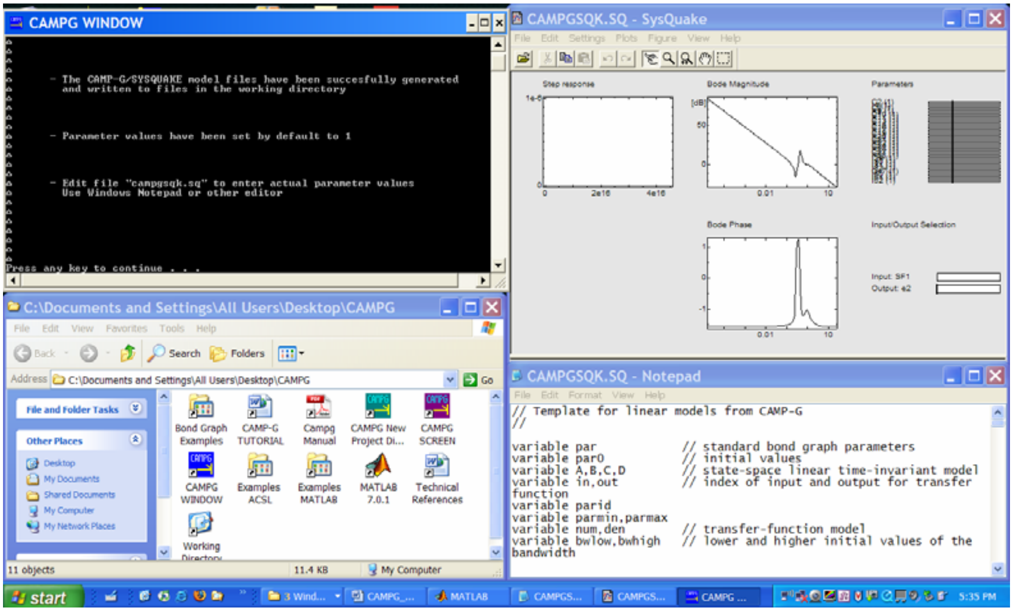
BOND: FROM

Fig. 1-13 CAMPG/SIMULINK interface with Bond Graph, State Space and Transfer Function.

1.7 The CAMPG/SYSQUAKE interface

The CAMPG/SYSQUAKE follows the same structure of others. The user enters the Bond Graph model in graphical form and then chooses the SYSQUAKE interface.

CAMPG will automatically link to SYSQUAKE as the two programs also share the same working space. The SYSQUAKE model keeps the same notation and names of the variables from the original bond graph. Shown below is the display of the CAMPG message window and the SYSQUAKE graphics window that is generated as CAMPG directs the SYSQUAKE display. There are four windows shown the CAMPG message window, the SYSQUAKE graphics window, the CAMPG icons and the SYSQUAKE model generated by CAMPG.



```
    - The CAMP-G/SYSQUAKE model files have been succesfully generated
      and written to files in the working directory



    - Parameter values have been set by default to 1



    - Edit file "campgsqk.sq" to enter actual parameter values
      Use Windows Notepad or other editor




Press any key to continue . . .
```

```
// Template for linear models from CAMP-G
//

variable par             // standard bond graph parameters
variable par0            // initial values
variable A,B,C,D         // state-space linear time-invariant model
variable in,out          // index of input and output for transfer
function
variable parid
variable parmin,parmax
variable num,den         // transfer-function model
variable bwlow,bwhigh    // lower and higher initial values of the
bandwidth
```

Fig. 1-14. CAMPG/SYSQUAKE interface

This is an interesting interface because once SYSQUAKE receives the model from CAMPG; the user is presented with a screen for time and frequency response that automatically can be display as the physical parameters change. SYSQUAKE allows the user to change the physical parameters by the use of sliders and see immediately the response in the time and frequency domain.

Chapter 2

CAMPG Basics

2.1 Introduction

PURPOSE OF THIS MANUAL

The first part of this manual provides an introduction to the many features of CAMPG. It begins with a general description of the purpose and capabilities of the package then it provides a detailed description of how to use the software. Once completing the example problems outlined in Section 3 and the tutorials of Section 6, the user should feel confident about generating a Bond Graph model using CAMPG and performing a simulation using a Digital Simulation Language (ACSL for example).

The manual outlines in Section 5 a detailed description of simulation using the CAMPG/ACSL system. A detailed explanation of the simulation procedure and runtime commands is given in the tutorials of Section 6. Linear and non-linear examples show how ACSL and CAMPG can be used together to solve dynamic systems problems.

DESCRIPTION OF CAMPG

CAMPG (Computer Aided Modeling Program - with Graphical Input) is a graphical preprocessor for Digital Simulation Languages. It provides the user with tools to construct a graphic display of a bond graph on the screen. CAMPG derives all the necessary equations from this bond graph and writes them to a convenient input file for the requested Digital Simulation Language.

Generating a bond graph model is relatively simple on CAMPG. The user can use the program to build the bond graph from the physical system. CAMPG will assign causality and provide descriptions of any errors that might exist in the bond graph. In this respect, CAMPG acts as a bond graph design tool as well as a Digital Simulation Language preprocessor.

The modeling and design process is enhanced by the constant monitoring of the model. CAMPG features allow the designer to get instantaneous information of the precision of the model because it can detect modeling problems such as derivative causality, algebraic loops, bond graph structure and other modeling problems that may prevent the generation of close form sets of differential equations.

CAMP AND CAMPG

The Computer Aided Modeling Program (CAMP) and its capabilities is the parent program of CAMPG. CAMP was designed to run on a wide range of minicomputers and PCs using standard displays that do not have graphics capabilities.

Using CAMP it is possible to generate models for simulation languages even if no color graphics capability were available in your PC or in a terminal attached to a minicomputer. The CAMP program can be used for this purpose. The bond graph model is entered by a description from the keyboard. The program is self-explanatory as it displays interactive instructions on the screen.

Using CAMP in the non-graphics mode will produce the same models generated using CAMPG. The output files used as input models for simulation languages in CAMP and CAMPG are completely compatible.

The difference between these two software packages is that instead of entering the bond graph graphically using the mouse as in CAMPG it is entered as a text description in CAMP. The graphical environment in CAMPG helps explore the model and its causality as it is being drawn on the screen. CAMP will do this with messages displayed on the screen. The individual equations and modeling problems can be examined directly. In CAMP these are presented to the user in the form of error or system messages. The CAMP program prompts the user for the necessary information and then builds the CAMPSL.CSL model file used as input to ACSL and other languages. CAMPG does this through a menu selection using the mouse and computer graphics capabilities that allow the user to enter the actual bond graph model on the screen.

CAMP can run on any monitor and attached to a minicomputer or mainframe requires an alphanumeric keyboard or any text ASCII terminal.

CAMPG runs on computers and terminals of high resolution. It requires a PC XT or AT type with a 640k of memory. It will run on 8088 based computers to the 80286, 80386 or 80486 computers. It requires an EGA or VGA monitor, a hard disk is recommended, a mouse and driver.

CAMP and CAMPG are fully supported programs with their respective documentation and installation instructions tailored to each individual type of computer.

2.2 How to Use CAMPG

STARTING CAMPG

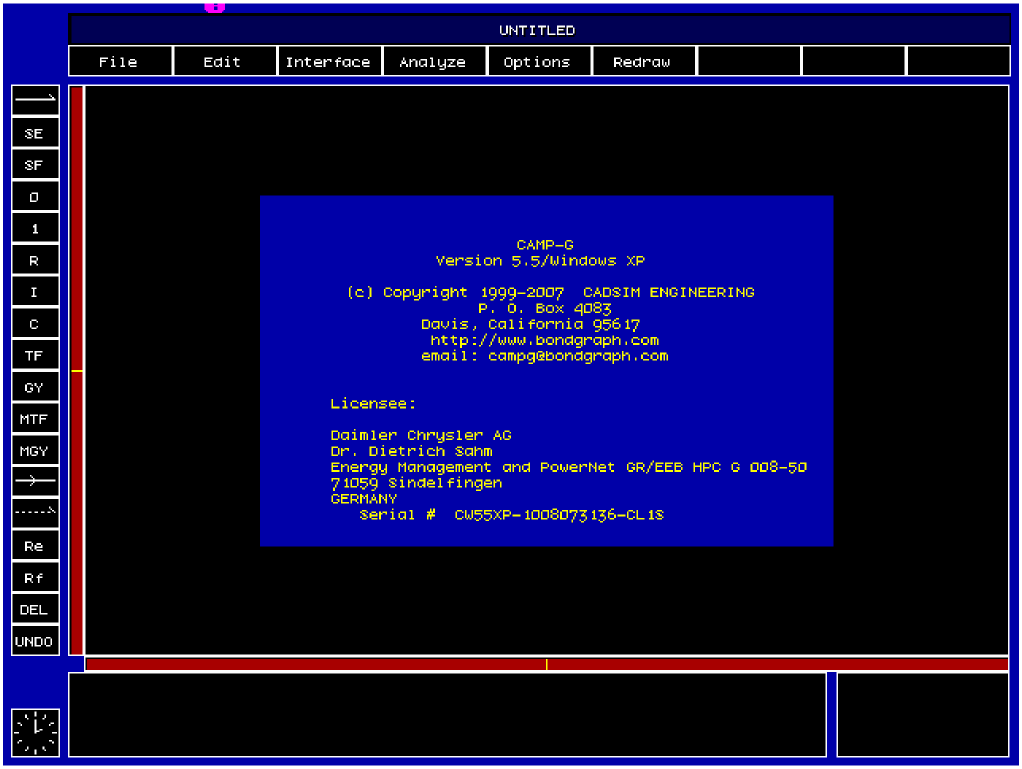
Start CAMPG by clicking on the CAMPG icon in the CAMPG desktop folder of the Programs START menu. Pressing any key or moving the mouse clears the initial logo and prepares the graphics screen for input. CAMPG automatically brings up the last SESSION.BG file if one exists. This way the user has the last model he worked on ready to go again or the screen can be cleared and start a new one.

CREATING A BOND GRAPH

The screen that appears as CAMPG starts is shown in Fig 2-1. There is a menu on the left that contains icons for the kinds of physical elements that can be used. There is a set of pull down menus at the top. These start with the keywords like EXIT, REDRAW, EDIT, FILES, OPTIONS, ANALYZE. The message dialogue box is at the bottom left and a status box on the bottom right corner. There are two yellow bars one horizontal the other one vertical. They are used to scroll the bond graph model in the horizontal and vertical direction.

This way the user can enter a bond graph that is bigger than the screen would display. All of the elements required to construct a bond graph are located on the left side of the screen in the vertical menu (Fig 2-1). The boxes contain the menu selections for a BOND, an EFFORT SOURCE (SE), and then a FLOW SOURCE (SF). Following these are the ZERO JUNCTION (0), the ONE JUNCTION (1), the physical elements RESISTOR (R), INERTIA ELEMENT (I), the CAPACITOR ELEMENT (C), the

CAMPG starting screen



CAMP-G
Version 5.5/Windows XP

(c) Copyright 1999-2007 CADSIM ENGINEERING
P. O. Box 4083
Davis, California 95617
http://www.bondgraph.com
email: campg@bondgraph.com

Licensee:

Daimler Chrysler AG
Dr. Dietrich Sahm
Energy Management and PowerNet GR/EEB HPC G 008-50
71059 Sindelfingen
GERMANY
Serial # CW55XP-1008073136-CL1S

Fig. 2-1 CAMPG Initial Screen

PLACING ELEMENTS

The menu of elements on the left side of the screen is used to place any of the elements (SE, SF, 0, 1, R, I, C, TR, GY) on the screen. Move the cursor to the desired box and click. Then move the cursor to the appropriate screen location and click again. The element will appear on the screen just beneath the cursor. The elements are placed following a grid that allows the bond graphs to be straight and with no distortion. The grid can be turned off by the user.

BONDING

Elements are connected with BONDS. Move the cursor to the BOND box, click, and then click consecutively on the two elements to be bonded. Power will flow from the first element selected to the second selected element or junction. The order in which the mouse is clicked determines the TO and FROM direction. The power flow half arrows are displayed with the respective bonds. Causality is assigned automatically and both power flow and causality displayed on the screen.

A complete Bond Graph can be created by placing all of the elements on the screen by selecting them from the vertical menu and moving them to the desired location. Next, select the BOND box and connect the elements with bonds. This method will be known as the SYSTEMATIC METHOD. Using this technique it is possible to create any desired bond graph. Another technique is the SEQUENTIAL METHOD. This means that the bonds are drawn immediately after a junction or an element has been placed. To do this, place the first two elements. Then bond these two by clicking on the first then on the second. Now place the third element and bond it to the second by clicking on the two elements. This method joins the 0 or 1 junctions with elements as the bond graph is being constructed.   Causality and power flow are assigned at the same time.

2.3 CAMPG FEATURES AND MENUS

The screen is divided into four sections. The top section contains the main menu key words. The left vertical icon set section is used to select the different elements. The bottom section has a dialogue window and a status window that tells the user what CAMPG is to do next. The rest and biggest section of the screen is the area used for the bond graph model display.

DIALOGUE BOX Comments about the current operation are written in the large box in the lower left corner.

STATUS BOX This box, located in the lower right corner, prompts the user for the next action. For example, when the user selects the BOND box, the STATUS BOX asks him to select the first element to be bonded.

QUICK DELETE This allows you to delete elements, bonds and their numbers one at a time. Just select the DEL box in the lower left hand corner and then click on the items to be deleted. The last item can be undeleted by selecting the UND (Undo), which is also located in the lower left corner.

PULL-DOWN MENUS

CAMPG uses pull-down menus located at the top of the screen (Fig 2-1) to facilitate bond graph construction, and Digital Simulation Language interface. A detailed explanation of each menu is shown below in the order in which they appear on the CAMPG screen.

EXIT This allows the user to exit the CAMPG program. The different selections in this menu allow the user to either exit TO DOS without creating any input files to the digital simulation languages, or to exit to a specific language.

TO ACSL Interface to the Advance Continuous Simulation Language (ACSL). It Creates the ACSL input file CAMPSL.CSL. This would also close the graphics session and start the editing phase. The editing phase is necessary to place any non-linearities or functions that either are user generated of they are part of a simulation language.

TO DSL/CSMP This option selects the interface to IBM's Dynamic Simulation Language or to CSMP (Continuous System Modeling Program. It also starts the editing phase of the DSL input file generated by CAMPG. This is the CAMPG.DSL file.

TO CSSL This option will produce an interface file for the CSSL-IV language.

REDRAW This selection is used to refresh and redraw the screen at any time.

EDIT This pull-down menu contains features that perform modifications and editing of bond graphs. It is used by clicking the cursor on the EDIT box, a sub-menu will be displayed. Click again on the desired selection. After the selection is made, the REQUESTED ACTION BOX will prompt you to select either the portion of the bond graph to be acted upon or other options that are displayed.

DELETE Four methods of deletion exist:

SINGLE One element only can be deleted. CAMPG will not allow you to delete a single element if a bond is attached because it considers the bond and the element as separate items. You could delete the bond and then the element separately.

GROUP It deletes an element and the attached bonds.

SEGMENT All items attached to the selected object will be deleted. It means delete all the structure that is continuously connected to the selected element or bond. Be careful, if your entire bond graph is connected, it is all one segment.

ALL It will delete everything on the screen including segments of graphs that may not be linked together.

After selecting the method of deletion, use the cursor to locate the portion of the bond graph to be acted upon. A different cursor will appear to warn the user that delete is on.

PICK This selection is used for copying elements, or segments to another location on the screen. It allows you to mark either a SINGLE (element) or an entire SEGMENT. Once the user has marked an element or a SEGMENT he can copy it to another place on the screen by moving the cursor to other location and clicking one of the left button.

PUT It is used to place the elements or segments that have been selected with PICK. So this option is automatically on after PICK has been selected. You can place last PICK item in any location.

MOVE Selection of MOVE allows you modify the shape of the bond graph because it can move elements and their attached bonds. For example if a 1 or a 0 junction is moved to different location on the screen its attached bonds will still be connected but their distance to the corresponding elements will be different thus changing the appearance of the bond graph. It can be used to make room for new elements of to change the aesthetic appearance of the bond graph model. Either a SINGLE section (element and its bonds) or an entire SEGMENT can be moved to a new location.

FILE This pull-down menu contains a number of files which CAMPG will create upon request. When a selection is made you are prompted to input a filename. Input any file name and press return. The files include LIST, EQUATIONS, RECORDS, AND CONFIG.

A detailed explanation of each file structure is contained in section 4.0 CAMPG FILES.

The FILES menu also contains functions, which allow you to manipulate existing files.

CONFIG This file stores the SET UP options for the entire CAMPG system. It contains settings for selected options. There is no need to edit this file unless there is problem with the system. Please consult your system manager.

SESSION CAMPG saves the current model under a SESSION.BG file so that it automatically loads the last bond graph model that was worked on. This selection allows for changing the name of the session file from its default SESSION.BG.

LOAD This selection is used to load any existing bond graph model from disk. These files have the .BG extension by default. The file is loaded and integrated to the current session existing on the screen. This will add the contents of a file to the current session without replacing the existing one.

STORE This is used to save the current bond graph in a file under any given name. To do this click the mouse on the

STORE button and type the new file name. The current bond graph model will be saved to that file.

LIST Internal file of CAMPG

RECORDS Internal file of CAMPG

EQUATIONS This file will contain the differential equations generated by CAMPG in the format that any FORTRAN or C program source code. It is intended for the user who is not using an existing simulation language but rather his own program. The contents of this file could be integrated in a Sub program that the user could modify and use as part of his own program.

OPTIONS

The following options are available under this pull-down menu:

STICKY If sticky is selected and set to -ON- you are able to select an element from the left hand menu and, until a different selection is made, each consecutive click will place that element on the screen. This is helpful when constructing large bond graphs.

It is also helpful if the user wants to place all the 1 and 0 junctions first. All junctions and elements of a chosen type could be placed and long as this option is on. This option also applies to other functions such as delete. The user can delete sequentially elements and bonds as long as this option is set to -ON-.

GRID This option helps to shape the bond graph to self align the elements and bonds with horizontal and vertical axis. There are three options within GRID.

VISIBLE- A grid point mesh is displayed on the screen. All elements and bonds will be automatically positioned and aligned with the visible grid points. This generates a very orthogonal, even drawing.

HIDE The grid points do not show up on the screen but GRID is still on.

OFF The elements and bonds are placed exactly at the cursor location. There is no grid alignment for bonds or elements. The bond graph is drawn to the exact locations selected by the user.

COLOR Colors can be assigned to all the elements, bonds, grid points and colors that modify the bond graph depending on error messages or modeling problems. To change the color of your selection click the mouse on the COLOR option and a menu containing the following selections will be displayed. Colors are changed by selecting one of this options and clicking the mouse on the color displayed on the color table.

BOND Bonds that join elements and junctions.

ELEMENT Single and multiport elements.

NUMBER Bond numbers.

MARKED Selected bonds and structures for moving to a different location on the screen.

GRID Grid points that help align the bond graph in the vertical and horizontal directions.

AMBIO Setting for the ambiguous causality and other problems with the bond graph structure.

DERIV Color of the derivative causality indicator.

OTHER Option for messages and other bond graph problems.

ANALYZE ANALYZE contains the features that makes CAMPG a design tool.. CAMPG is able to detect errors in bond graphs. When an error is detected, the element or bond is given a red color. In order to understand in detail what those changes in color as the graph is being drawn the following option provide an inside view of the bond graph.

EXPLAIN

This feature gives explanations of the bonds and elements. Once EXPLAIN is selected a stethoscope shape will be the cursor on the screen. This indicates that the user will "listen" to what is wrong with the bond graph by clicking in the red bonds or elements and seeing a message displayed on the bottom window (DIALOGUE BOX). This is useful when there is an error (red element or bond) in the bond graph. The user could click in any other part of the bond graph that does not have the warning color. A massage indicating the status of that element or bond will be displayed.

PEEK

This feature allows you to examine the equations throughout the bond graph structure. These equations can be examined at each bond, element or junction. After selecting PEEK move the cursor, which is now an "eye", to any element and click. The describing equations will appear on the screen underneath the cursor.

MEMORY

This brings up general accounting information concerning the current CAMPG session computer usage. It helps evaluate the memory size and computer resources necessary to complete the current model. Limitations on memory and resources will determine the size of the model that a particular computer could handle.

SCROLL BARS There are two bars in between the main drawing area and the left side menu as well as the bottom DIALOGUE BOX. These bars are displays as yellow bars. They can be used for scrolling the bond graph sideways or backwards or forwards. This indicates that the bond graph model is generated in a window that can be moved around in order to generate large bond graphs.

QUICK DELETE This feature allows the use to delete an element or bond quickly without going to the EDIT menu. It will delete a single element or bond unless the STICKY option is set to on in which case it could delete more that one element or bond.

UNDELETE The undelete feature allows the user to recover the last deleted elements, bonds, groups or segments. It displays quickly the bond graph the way it was before the delete action.

2.4 Generating Bond Graph Models

Once you have CAMPG installed on a computer the user is ready to generate a bond graph model with graphical input. The symbol (CUR) means to select with the cursor clicking the mouse. The symbol <CR> means press ENTER from the keyboard. There are two methods of building the bond graph in CAMPG.

One method is called the SEQUENTIAL METHOD and the second one is a SYSTEMATIC METHOD. Both of these are discussed in detail below.

SYSTEMATIC METHOD OF BOND GRAPH CONSTRUCTION

The approach is to build the bond graph models by entering all the 1 junctions, all 0 junctions first and then building the bond graph in a structured and methodical manner. Power flow and causality assignments are done as the bonds join the junctions (0 and 1) and the physical elements.

An example of a single degree of freedom system will illustrate this method. The following figures show the physical system and the bond graph for the damped oscillator. CAMPG will be used to construct the bond graph systematically and create the required ACSL input file.

Single degree of freedom oscillator

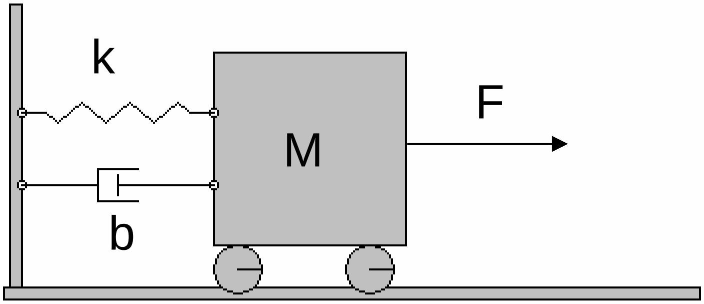


Fig 2-2 Physical System

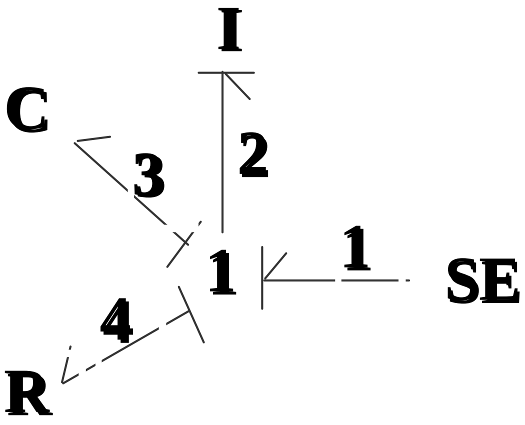


Fig. 2-3 Simple Bond Graph

This graph was generated using the sequence of actions and commands shown below:

CAMPG <CR>	Command that starts CAMPG and brings up the logo containing the user name and the license number. Please refer to this number for updates.
(space bar) <CR>	This clears the screen preparing it for a drawing. Pressing any other character or movement of the mouse will do the same. The last SESSION.BG file will be automatically displayed, if no session file, the screen will be blank.
EDIT(CUR)	These next steps are done to clear the session file and allow the user to start fresh with a new model. If there is no previous SESSION.BG file, this step is snot necessary.

DELETE (CUR)
ALL (CUR)
YES (CUR)

1 (CUR) There is a button on the left icon menu which has a (1) in it. This is the ONE junction in the bond graph. Click the mouse on these buttons and the computer will store the element to a buffer. Then to place it on the screen it is necessary to click the mouse in any desired screen location.

(Middle of screen) (CUR) Place the (1) on the screen by moving the cursor to the desired location and clicking.

C (CUR) Now select a (C) element by clicking the mouse while the cursor is on the C button on the elements menu. Place this to the left of the (1) by moving the cursor and clicking the mouse. The distance is arbitrary.

I (CUR) Select an (I) and place it to the right of the (1).

R (CUR) Select an (R) and place it above the (1).

(BOND SYMBOL) (CUR) Go to the top box on the left menu. This is the bond symbol. Click here. Notice that the PROMPT BOX reads BOND:FROM. It is asking where you would like to start your first bond.

1 (screen) (CUR) Click on the (1) element on the screen.

C (screen) (CUR) Click on the (C) element on the screen. A bond should appear between these two elements. Notice that both power and causality are assigned.

1 (screen) (CUR)

I (screen) (CUR) This should create a bond from the (1) element and the (I) element.

1 (screen) (CUR)

R (screen) (CUR) This should create a bond between the (1) element and the (R) element.

SEQUENTIAL METHOD OF BOND GRAPH CONSTRUCTION

The SEQUENTIAL method builds the bond graph by joining the elements with bonds immediately after being placed on the screen. Power flow is assigned from the element chosen by clicking the mouse to the element selected next. Causality assignment is automatic as each bond is drawn. The program properly colors the incomplete bond junctions, algebraic loops, and derivative causality giving the user immediate feedback on how the construction of the bond graph model is going. If the generation of the bond graph is completed and still there are colored bonds, it means that CAMPG detects modeling problems such as algebraic loops, incomplete or incompatible bond graphs and derivative causality.

Let's use the same example of the previous section to illustrate this technique.

CAMPG <CR> Start CAMPG and brings up the logo containing the user name and the license number. Please refer to this number for maintenance and updates.

(space bar) <CR>
This clears the screen preparing it for a drawing. Any other character or movement of the mouse will do the same.

EDIT (CUR)
The next three steps clear the session file. If you have no previous SESSION.BG file. These steps are not necessary.

DELETE (CUR)
ALL (CUR)
YES (CUR)

1 (CUR)
There is a box on the left icon menu which has a (1) in it. This is the ONE junction in the bond graph. Pick the 1 with the mouse.

(Middle of screen) (CUR)
Place the (1) on the screen by moving the cursor to the middle and clicking the left button of the mouse. The model can start in any location of the screen.

C (CUR)
Now select a (C) element by clicking the mouse while the cursor is on the C button on the elements menu. Place this to the left of the (1) by moving the cursor and clicking the mouse. The distance is arbitrary.

(CUR)
At this point you will see on the Status Box the message "Bond: from" and the cursor turned to a small circle and an arrow pointing left. Click on the 1 junction. The cursor will change direction as a circle and an arrow pointing right. The Status Box reads "Bond:

	to". Click the cursor on the C element or as close to it as you can. The bond that joins the junction and the element will be displayed along with a bond number and the causality assignment.
I (CUR)	Select an (I) and place it to the right of the (1).
(CUR)	Status Box reads "Bond: from" and the cursor turned to a small circle and an arrow pointing left. Click on the 1 junction. The cursor again changes direction as a circle and an arrow pointing right. The Status Box reads "Bond: to". Click the cursor on the I element or as close to it. The bond that joins the junction and the element will be displayed with its corresponding bond number one higher than the previous one and causality assignment.
1 (screen) (CUR)	
I (screen) (CUR)	This should create a bond from the (1) element and the (I) element.
R (CUR)	Select an (R) and place it above the (1).
(CUR)	
1 (screen) (CUR)	Click on the (1) element on the screen.
R (screen) (CUR)	Click on the (R) element on the screen. A bond should appear between these two elements.

1 (screen) (CUR)

R (screen) (CUR) — This should create a bond from the (1) element and the (R) element.

The bond graph has been created. Try using some of the other features that CAMPG offers. For example, look at the equations by selecting ANALYZE then PEEK, then selecting any of the elements. Try moving the bond graph by selecting EDIT then MOVE, then SEGMENT. Now click on any section of the bond graph. One more click somewhere else will move the whole bond graph to a new location.

The user will realize at this point it is simple to create a bond graph model using CAMPG. It is also simple to modify the graph once it has been built. The most used operations for this are the delete and placement of new elements. The placement of new elements can be easily handled as explained in the example above. The deletion of elements or bonds has a couple of alternatives. One is the quick delete operation that deletes one element of bond. The one is the delete options under the EDIT menu. The user can practice these forms of deletion explained in more detail below.

QUICK DELETE — Use of this button will delete an element, a bond, a loose element of or bond junction. The user clicks the mouse on this button, the cursor will change for this mode and then the user picks the element or junction to be deleted by clicking the mouse on that location.

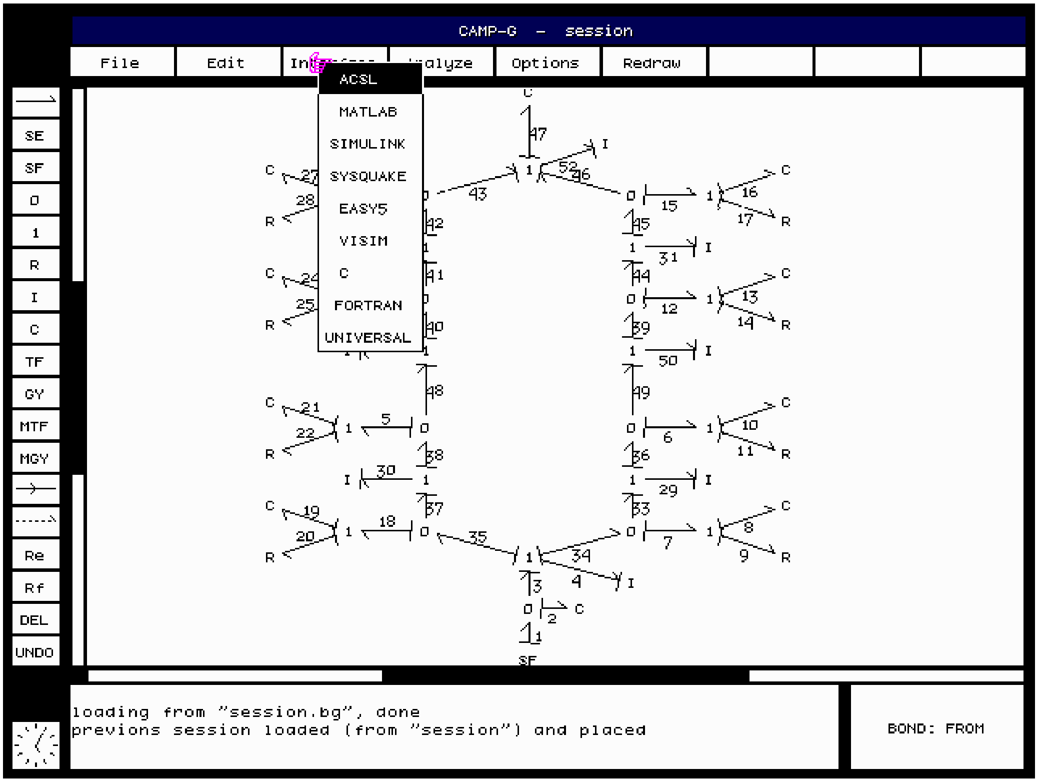
EDIT/DELETE The DELETE button under the EDIT menu allows for several selections. DELETE SINGLE for just one element, GROUP to delete an element (I, C, R, TF, GY, 0, 1,) and all its attached bonds at the same time. , SEGMENT will delete the whole structure attached to the selected element or junction. Finally ALL will delete every bond graph existing on the screen at the time. Clears the whole screen.

2.5 Interfacing with a Digital Simulation Language

ACSL INPUT FILE PREPARATION

CAMPG can be used as a preprocessor for Digital Simulation Languages or the user's own program. As such, it creates the necessary input files for these languages. Selection of the EXIT menu of CAMPG (upper left hand side) will display the different languages for which CAMPG will create an input file in source code form. Select the appropriate digital simulation language by clicking the mouse on the appropriate box. The required input file will be created and placed in your directory. The menu with the selection of the Simulation Language.

CAMPG simulation language interface menu



```
loading from "session.bg", done
previons session loaded (from "session") and placed
```

```
BOND: FROM
```

Fig. 2.4 CAMPG Simulation Language Interface Menu

EXIT CAMPG

Once a simulation language is selected, CAMPG will proceed to generate the necessary files to produce an interface to the Simulation Language and it will continue with a menu that allows the user to edit and complete the input file and other options discussed below.

However, the user may want to exit CAMPG without creating an input file to a digital simulation language, select EXIT in the upper left corner. This will automatically save the current bond graph to a session file named by default, as **SESSION.BG** The user can save the file under another name. This is done using the FILES menu and entering the file name under the STORE button. The file will be saved with another name. This is useful also to save a session file for use in the future. The process is change the name either outside of CAMPG at the Command prompt or by using the STORE button under the FILES menu.

CAMPG can generate input files for ACSL and other simulation languages after the selection is made from the EXIT menu. Once the file generation takes place, a menu will be displayed. Shown below is a summary of these steps.

EXIT (CUR) this button will allow the generation of the input files for a simulation language as well as exiting to the DOS environment. The user may select the appropriate button that corresponds to that language or to DOS. Regardless of the selection, CAMPG saves the bond graph model drawing to a file called SESSION.BG before exits the program.

TO ACSL (CUR) clicking the mouse on this button will cause the computer to generate an ACSL input file. CAMPSL.CSL is the ACSL input file. Upon completion and saving of the bond graph file, the computer will print a menu that gives the user selections to how to proceed.

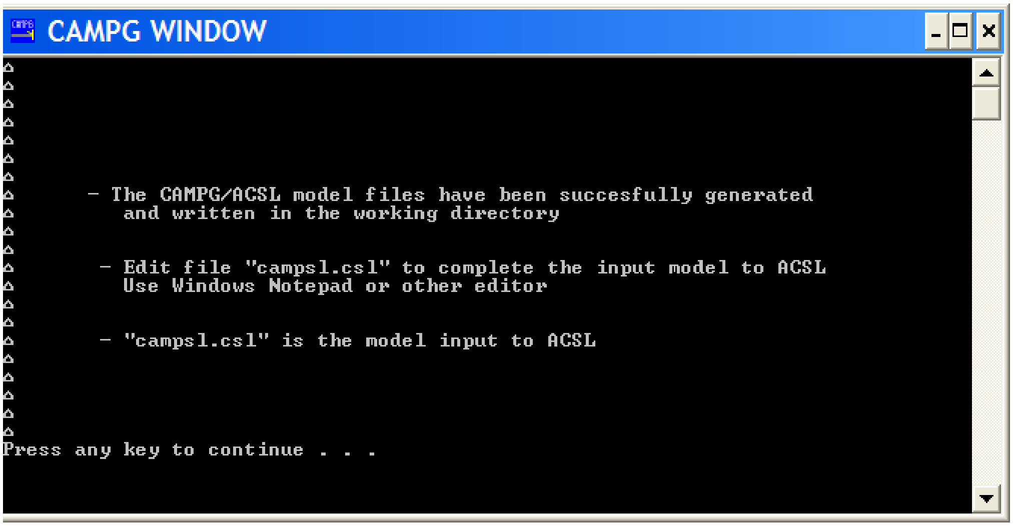
The computer will display a message like:

WORKING..... ONE MOMENT PLEASE ......
:
:
:

:
:

EDIT FILE CAMPSL.CSL

And then will display:



```
       - The CAMPG/ACSL model files have been succesfully generated
         and written in the working directory

        - Edit file "campsl.csl" to complete the input model to ACSL
          Use Windows Notepad or other editor

        - "campsl.csl" is the model input to ACSL



Press any key to continue . . .
```

Fig 2-5 CAMPG/ACSL message display.

The message reminds the user that CAMPSL.CSL is the ACSL input file generated by CAMPG. This file needs to be edited to enter parameter values, non-linearities and simulation control statements.

Edit CAMPSL.CSL This option will automatically place the user on the editor of choice. This can be EDT the VAX editor running on the PC, it can be a word processor with ASCII files editing capability such as Wordperfect, Microsoft Word and others. The different editors for a particular system could be accessed automatically.

RUN ACSL with CAMPSL.CSL

This option links the ACSL system to the CAMPG generated model file CAMPSL.CSL. and produces a CAMPSL.EXE

Execute CAMPSL.EXE

This option is useful if we are studying a model that has been translated, compiled, linked and executed previously. This may be the case where a simulation may be done with different parameters and different plots on the same model. The ACSLCLG CAMPSL command means run ACSL with CAMSPSL.CSL as input. Note that the CSL file attribute is not necessary.

Chapter 3

CAMPG and Matlab

3.1 Introduction

This document is to help the user learn how to use CAMPG in conjunction with Matlab. This document will tell and show the user how to create a bond graph in CAMPG and then interface that bond graph with Matlab so the system being modeled can be simulated. This document will also help the user get a better understanding of the files that are created when CAMPG is interfaced with Matlab and how to use them to get what is required of the project.

Using CAMPG in conjunction with Matlab makes for a very powerful set of computer modeling and simulation tools. With the proper creation of a bond graph CAMPG can write the files that Matlab will user to run computer simulations of the system that is modeled by the bond graph.

3.2 Interfacing CAMPG with Matlab

Interfacing CAMPG with Matlab is a very simple procedure that is very fast. Before the interfacing can take place, a bond graph needs to be created in CAMPG that represents the system being modeled. To create a bond graph follow the steps below.

1. Start CAMPG, by double clicking on the icon as seen in *Fig. 3-1*. This icon is located in the CAMPG desktop folder or in the CAMPG Start Menu/ All programs.

2. Either move the mouse or press the "Enter" key. This will clear the screen from *Fig. 3-2 to Fig. 3-3.* Now CAMPG is ready for you to enter the bond graph or work with an existing one.

3. Create the bond graph. This procedure is explained in detail in each of the examples in sections 3.7, 3.8 and 3.9.

   Once the bond graph is created and it is free from errors, CAMPG is ready to interface with Matlab.

4. Select the menu called "Interface". A drop down menu should appear as in *Fig. 3-4*.

5. Choose the menu choice called "Matlab".

   Once this has been done, CAMPG will display something similar to what is seen in *Fig. 3-5*. Press the space bar and CAMPG will continue. Then CAMPG will exit and the user will be at the desktop with all three of the files it just created open and ready to have initial conditions, time interval, and element values input along with what ever else the system requires to be accurate.

CAMPG Executable Icons

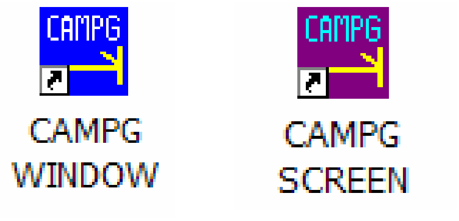
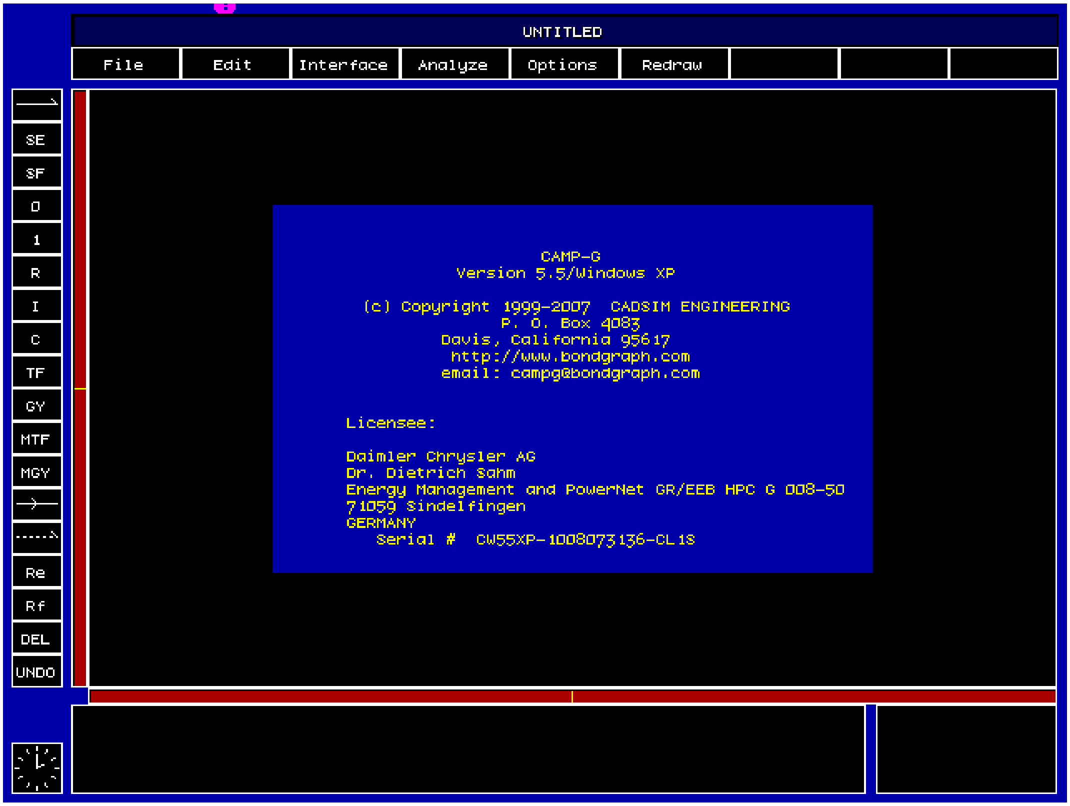


Fig. 3-1 CAMPG starting icon

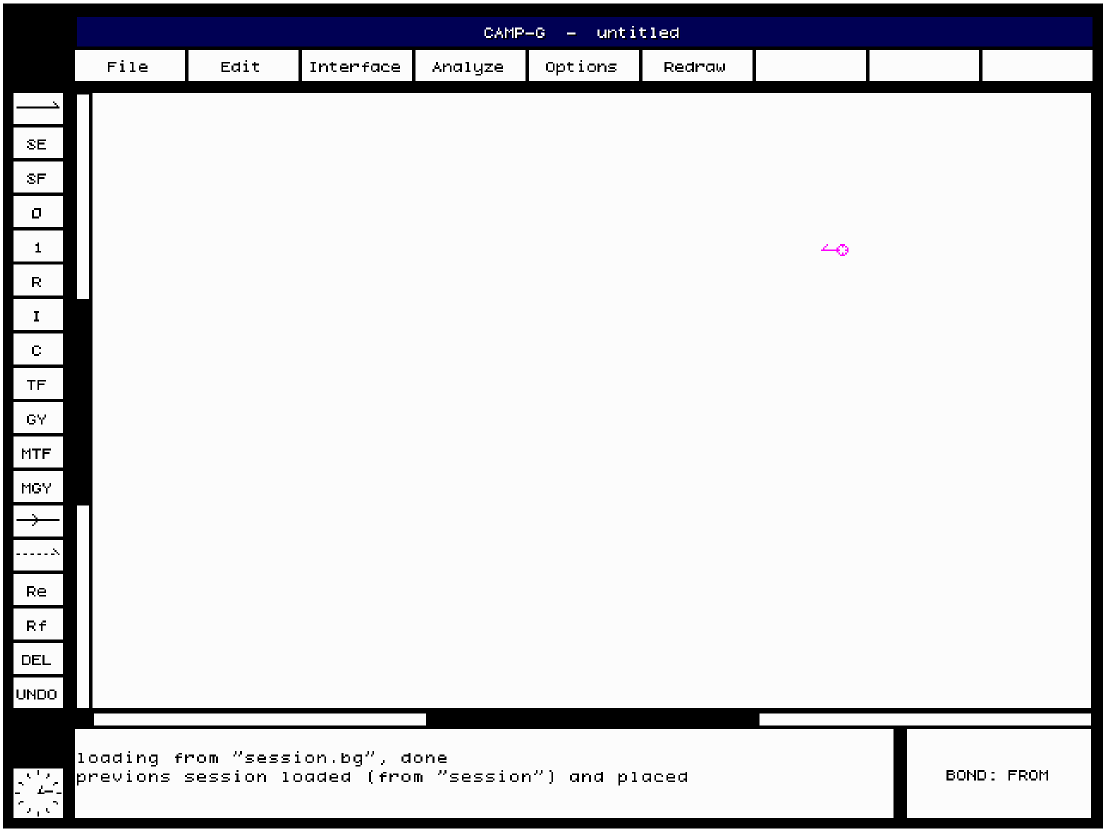
CAMPG Initial Screen



```
CAMP-G
Version 5.5/Windows XP

(c) Copyright 1999-2007  CADSIM ENGINEERING
P. O. Box 4083
Davis, California 95617
http://www.bondgraph.com
email: campg@bondgraph.com


Licensee:

Daimler Chrysler AG
Dr. Dietrich Sahm
Energy Management and PowerNet GR/EEB HPC G 008-50
71059 Sindelfingen
GERMANY
   Serial #  CW55XP-1008073136-CL1S
```

Fig. 3-2 CAMPG Starting Screen

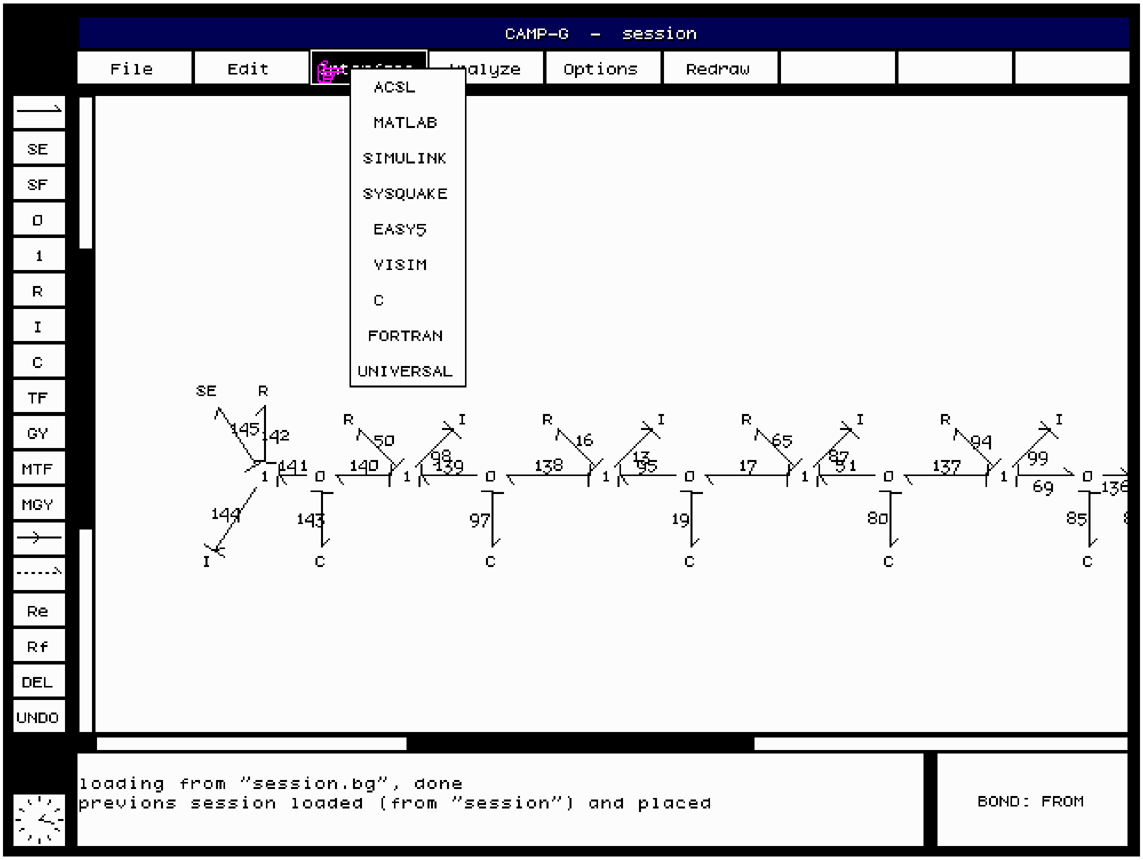
CAMPG Working Screen



```
loading from "session.bg", done
previons session loaded (from "session") and placed
```

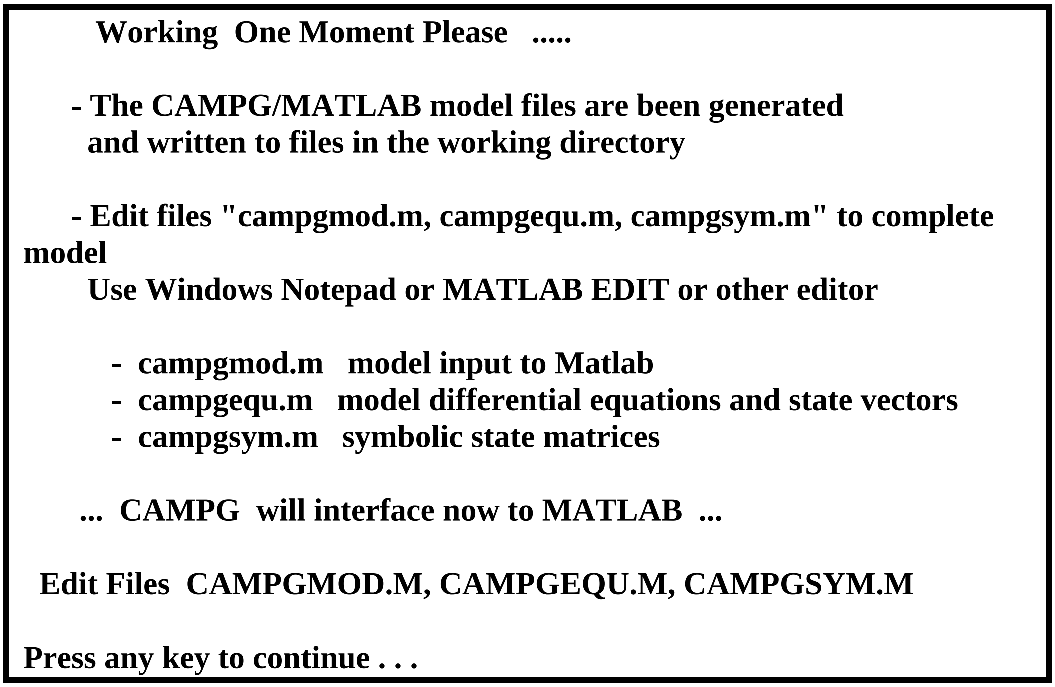
Fig 3-3 CAMPG Desktop Working Screen

CAMPG Interface Menu



```
loading from "session.bg", done
previons session loaded (from "session") and placed
```

Fig 3-4 CAMPG Simulation Language Interface Menu



```
         Working  One Moment Please   .....

      - The CAMPG/MATLAB model files are been generated
        and written to files in the working directory

      - Edit files "campgmod.m, campgequ.m, campgsym.m" to complete
model
        Use Windows Notepad or MATLAB EDIT or other editor

            -  campgmod.m   model input to Matlab
            -  campgequ.m   model differential equations and state vectors
            -  campgsym.m   symbolic state matrices

       ...  CAMPG  will interface now to MATLAB  ...

  Edit Files  CAMPGMOD.M, CAMPGEQU.M, CAMPGSYM.M

Press any key to continue . . .
```

Fig. 3-5 CAMPG message window

3.3 Files Created During Interfacing and Descriptions

When interfacing CAMPG with Matlab, CAMPG creates three files that the user uses to run the computer simulation. The three files are 1) campgmod.m, 2) campgequ.m and 3) campgsym.m. These files are very useful as will be seen below. This is a description of the structure of each of the files along with a description of how to implement and how to modify these files to model the system correctly.

The first two files mentioned are used in conjunction with each other, while the third file is used by itself. The first file is the main simulation file, while the second file is a simple function file that contains the entire dynamic system for the bond graph model. The first file is run from the Matlab command prompt. When it runs, it sets all the initial conditions, bond graph elements, inputs and the time interval. Then it calls the second file during the integration process and calculates the integrals over the set time span. Then it outputs the desired data in a graphical format, i.e. a graph.

The third file is usually used by itself. This file specializes in determining the transfer functions. This file uses the state space form seen below:

$$\begin{aligned} \mathbf{y'} &= \mathbf{Ax} + \mathbf{Bu} \\ \mathbf{y} &= \mathbf{Cx} + \mathbf{Du} \end{aligned}$$

All the user needs to do is to un-remark the appropriate lines and then input the desired number for the row that it will create in the state space matrix.

NOTE: There is one other file that CAMPG creates. This file is called **esandfs.m**. This file is not created every time CAMPG is interfaced with Matlab, it is created once, during installation of CAMPG. The location of this file is seen below:

<*source drive*>\matlab\toolbox\matlab\general\esandfs.m

The purpose of this file will be described later in this section.

CAMPGMOD.M

This file is used in conjunction with the file called "campgequ.m". After CAMPG has been interfaced with Matlab, this file is created.

The user only needs to make a few minor changes to this file to make it usable. The user must do the following:

1. Enter the values for the bond graph elements.

2. Enter the values for the inputs.

3. Enter the simulation time interval.

4. Create the plotting commands to plot what is required to be monitored.

Once these 4 things have been done, the simulation can take place.

This example listing is the listing for the linear example that is seen in section 3.7. The only difference between this listing and the one seen in section 3.7 is that this one has not yet been edited by the user. This is exactly the way this file would look just after the interfacing with Matlab has been done. As seen here, the sections of the file are very clear and straight forward.

Listing of campgmod.m

```
%    CAMPG/MATLAB - GENERATED MODEL DESCRIPTION:
%      The following files have been generated
%      campgmod.m  => m file containing model parameters
%                    intial conditions, sources and simulation controls
%      campgequ.m  => m function containing the system
%                    first order differential equations
%      campgsym.m  => m file containing system matrices in symbolic form
%
%    For simulation and control, edit these files
%     Enter values for physical parameters, initial
%     conditions,inputs and time controls
%     in places where the ?? marks appear
%     Standard generalized variables in Bond Graph notation used.
%
%......CAMPGMOD.M - MATLAB MODEL INPUT FILE  ......
  clear
% ......  Initial conditions  ........
             Q9IN= ?? ; Q3IN= ?? ;
             P11IN= ?? ; P6IN= ?? ;
  initial = [Q9IN; Q3IN; P11IN; P6IN] ;
```

```
% ......System Physical Parameters........
  global C3 R4 I6 C9 R10 I11
             C3 = ?? ;  R4 = ?? ;
             I6 = ?? ;  C9 = ?? ;
             R10 = ?? ;  I11 = ?? ;
% ...... External inputs se(t), sf(t) ......
  global SF1
             SF1 = ?? ;
%..... Simulation Time Control .....
             t0= ?? ;   %  Initial Time
             tf= ?? ;   %  Final Time
             tspan= [t0 tf];
%.....  Define Outputs .....
  global TIME STEP EFFORTS FLOWS
  STEP=1;
% ......  Computer Simulation ......
%  Solution of system equations using Matlab "ode23 or ode45" function
%  The "campgequ.m" function contains the system differential
%  equations in state variable form.
%
%  It returns the vector [t,p-q] where:
%   t = time and p-q = vector of state variables
%   [t,p_q] is a column vector with rows [t, p_q(1) p_q(2)  p_q(3) ...]
  [t,p_q] = ode23('campgequ',tspan,initial);
%          Q9= p_q(1) ; %          Q3= p_q(2) ;
%          P11= p_q(3) ; %          P6= p_q(4) ;
% State variables vector
% p_q = [Q9; Q3; P11; P6] ;
%
% Sample Matlab structure for plotting simulation results (state variables)
%  figure(1)
%  subplot (211),plot(t,p_q(:,1),'b'),grid
%  title(' Variable p_q(:,1) (stored in column 1),color blue')
%  ylabel ('p_q(1) (units)'),xlabel('Time (seconds)')
%  subplot (212),plot(t,p_q(:,2),'m'),grid
%  title(' variable p_q(:,2) (stored in column 2), color magenta')
%  ylabel ('p_q(2) (units)'),xlabel('Time (seconds)')
%
% Sample structure for plotting Output Variables as defined in "campgequ.m"
%   Example:  If the efforts and flows were defined as:
%    EFFORTS(STEP,:) = [e5 e11 e4];
%    FLOWS(STEP,:)  = [f2 f9  f8];
%  figure(2)
%  Plot e11 vs TIME (Second column of "EFFORTS" vector)
%   subplot (211), plot (TIME,EFFORTS(:,2),'b'),grid
%   title(' Effort variable of vector "EFFORTS(:,2)" stored in column 2')
%  Plot f8 vs time  (Third column of "FLOWS" vector)
%   subplot (212), plot (TIME,FLOWS(:,3),'m'),grid
%   title(' Flow variable of vector "FLOWS(:,3)" stored in column 3')

            %..........BOND GRAPH NOTATION.............
          %  GENERALIZED VARIABLES BOND GRAPH NOTATION :
%---------------------------------------------------------------------
%                      MECHANICAL         ELECTRICAL    HYDRAULIC
%              | TRANSLATION| ROTATION  |            |
%--------------|------------|-----------|------------|----------------
%E (Effort)    |Force       |Torque     |Voltage     |Pressure
%F (Flow)      |Velocity    |Ang Vel.   |Current     |Volume Flow Rate
%Q (Gen Disp)  |Displacement|Angle      |Charge      |Volume
%P (Gen Momentum)|Momentum  |Ang.Moment.|Flux Linkage|Pressure Moment.
%--------------------------------------------------------------------
% TF (M) (Transformer Modulus)      SE Source Effort
% GY (R) (Gyrator Modulus)          SF Source Flow
%--------------------------------------------------------------------

            %********************    ********************
            %....... BOND GRAPH ANALYSIS .......

%SYSTEM  DESCRIPTION:


% POWER FLOW:
% BOND    FROM                               TO
% ----    ----                               --
%   1   SF_1                               0_1_2_5
%   2   0_1_2_5                            1_2_3_4
%   3   1_2_3_4                            C_3
%   4   1_2_3_4                            R_4
%   5   0_1_2_5                            1_5_6_7
%   6   1_5_6_7                            I_6
%   7   1_5_6_7                            0_7_8_11
%   8   0_7_8_11                           1_8_9_10
%   9   1_8_9_10                           C_9
%  10   1_8_9_10                           R_10
%  11   0_7_8_11                           I_11

% CAUSALITY FLOW:

% NOTE:  FROM -----| TO

% BOND    FROM                               TO
% ----    ----                               --
%   1   0_1_2_5                            SF_1
%   2   1_2_3_4                            0_1_2_5
%   3   C_3                                1_2_3_4
%   4   R_4                                1_2_3_4
%   5   0_1_2_5                            1_5_6_7
%   6   1_5_6_7                            I_6
%   7   0_7_8_11                           1_5_6_7
%   8   1_8_9_10                           0_7_8_11
%   9   C_9                                1_8_9_10
%  10   R_10                               1_8_9_10
%  11   0_7_8_11                           I_11


% End of model
```

What follows is the same file seen above, but this time the file has been broken down into easier to see sections. Some of the file was excluded from this second listing. This was done because the only parts that are going to be show here are the parts that the user may have to change.

Initial Conditions

```
% ......  Initial conditions  ........
Q9IN= ?? ; Q3IN= ?? ;
P11IN= ?? ; P6IN= ?? ;
initial = [Q9IN; Q3IN; P11IN; P6IN] ;
```

System Physical Parameters

```
% ......System Physical Parameters........
global C3 R4 I6 C9 R10 I11
C3 = ?? ;  R4 = ?? ;
I6 = ?? ;  C9 = ?? ;
R10 = ?? ;  I11 = ?? ;
```

External Inputs

```
% ...... External inputs se(t), sf(t) ......
global SF1
SF1 = ?? ;
```

Simulation Time Control

```
%..... Simulation Time Control .....
t0= ?? ;   %  Initial Time
tf= ?? ;   %  Final Time
tspan= [t0 tf];
```

Defining Outputs

```
%.....  Define Outputs .....
global TIME STEP EFFORTS FLOWS
STEP=1;
```

Call to Integration Function and campgequ.m

```
[t,p_q] = ode23('campgequ',tspan,initial);
```

Sample Plotting Commands

```
        % Sample Matlab structure for plotting simulation results (state
variables)
        %  figure(1)
        %  subplot (211),plot(t,p_q(:,1),'b'),grid
        %  title(' Variable p_q(:,1) (stored in column 1),color blue')
        %  ylabel ('p_q(1) (units)'),xlabel('Time (seconds)')
        %  subplot (212),plot(t,p_q(:,2),'m'),grid
        %  title(' variable p_q(:,2) (stored in column 2), color magenta')
        %  ylabel ('p_q(2) (units)'),xlabel('Time (seconds)')
        %
        % Sample structure for plotting Output Variables as defined in
"campgequ.m"
        %   Example:  If the efforts and flows were defined as:
        %    EFFORTS(STEP,:) = [e5 e11 e4];
        %    FLOWS(STEP,:)     = [f2 f9  f8];
        %  figure(2)
        %  Plot e11 vs TIME (Second column of "EFFORTS" vector)
        %   subplot (211), plot (TIME,EFFORTS(:,2),'b'),grid
        %   title(' Effort variable of vector "EFFORTS(:,2)" stored in column
2')
        %  Plot f8 vs time  (Third column of "FLOWS" vector)
        %   subplot (212), plot (TIME,FLOWS(:,3),'m'),grid
        %   title(' Flow variable of vector "FLOWS(:,3)" stored in column 3')
```

CAMPGEQU.M

This is the file that contains the entire dynamic system. This file is called by the first file, campgmod.m, when the system is ready to be integrated. This file will send the calculated derivatives of the states to the integrating engine, which in turn will then send the newly determined states back to the first file, campgmod.m.

This example listing is the listing for the linear example that is seen in section 3.7. The only difference between this listing and the one seen in section 3.7 is that this one has not yet been edited by the user. This is exactly the way the this file would look just after the interfacing with Matlab has been done. As seen here, the sections of the file are very clear and straight forward.

Listing of campgequ.m

```
   function p_qdot = campgequ(t,p_q)
%  ...........campgequ.m   CAMPG/MATLAB function ...........
%  System differential equations, state Vectors
%
  global C3 R4 I6 C9 R10 I11
  global SF1
  global TIME STEP EFFORTS FLOWS
% System Differential Equations-First Order Form
%...... Define State Variables ......
        Q9= p_q(1) ;        Q3= p_q(2) ;
        P11= p_q(3) ;        P6= p_q(4) ;
% State variables vector
% p_q = [Q9; Q3; P11; P6] ;
%...... Define derivatives (dp,dq) and output variables (e,f) ......
        f1=SF1 ;                            e3=Q3/C3 ;
        f6=P6/I6 ;                          f7=f6 ;
        e9=Q9/C9 ;                          f11=P11/I11 ;
        f5=f6 ;                             f8=f7-f11 ;
        f9=f8 ;                             f10=f8 ;
      dQ9=f9 ;                              f2=f1-f5 ;
        f3=f2 ;                             f4=f2 ;
        e10=f10*R10 ;                     dQ3=f3 ;
        e4=f4*R4 ;                          e8=e9+e10 ;
        e11=e8 ;                          dP11=e11 ;
        e2=e3+e4 ;                          e5=e2 ;
        e7=e8 ;                             e1=e2 ;
        e6=e5-e7 ;                        dP6=e6 ;

% ... Build vector of derivatives p_qdot(n)...
%        p_qdot1) = dQ9 ; %        p_qdot2) = dQ3 ;
%        p_qdot3) = dP11 ; %        p_qdot4) = dP6 ;
% Derivatives vector
  p_qdot = [dQ9; dQ3; dP11; dP6] ;

% ...  Define output vectors (efforts,flows)...
% Sample Structure. Add any effort, flow or other variables to be plotted
% to the following "EFFORTS" or "FLOWS" vectors
% Activate in "campgmod.m" suggested structure of graphical output
%  TIME(STEP,1)=t;                % Define time vector
%  EFFORTS(STEP,:) = [e5 e11 e4]; % Define efforts vector
%  FLOWS(STEP,:)   = [f2 f9  f8]; % Define flows vector
%  STEP=STEP+1;
%
% In "campgmod.m" the following structure is included
% Sample structure for plotting Output Variables as defined in "campgequ.m"
%   Example:  If the efforts and flows were defined as:
%    EFFORTS(STEP,:) = [e5 e11 e4];
%    FLOWS(STEP,:)   = [f2 f9  f8];
%  figure(2)
%  Plot e11 vs TIME (Second column of "EFFORTS" vector)
%   subplot (211), plot (TIME,EFFORTS(:,2),'b'),grid
%   title(' Effort variable of vector "EFFORTS(:,2)" stored in column 2')
%  Plot f8 vs time  (Third column of "FLOWS" vector)
%   subplot (212), plot (TIME,FLOWS(:,3),'m'),grid
%   title(' Flow variable of vector "FLOWS(:,3)" stored in column 3')
```

What follows is the same file seen above, but this time the file has been broken down into easier to see sections. Some of the file was excluded from this second listing. This was done because the only parts that are going to be show here are the parts that the user may have to change.

Global Declaration

```
global C3 R4 I6 C9 R10 I11
global SF1
global TIME STEP EFFORTS FLOWS
```

This section is needed so this file will recognize the parameters that the user defined in this first file called "campgmod.m"

Defining the State Variables

```
% System Differential Equations-First Order Form
%...... Define State Variables ......
Q9= p_q(1) ;         Q3= p_q(2) ;
P11= p_q(3) ;        P6= p_q(4) ;
```

This section is need for the next section. This section sets the values for the state variables that are used in the equations in the following section.

Derivative and Output Variable Equations

```
%...... Define derivatives (dp,dq) and output variables (e,f) ......
            f1=SF1 ;                            e3=Q3/C3 ;
            f6=P6/I6 ;                          f7=f6 ;
            e9=Q9/C9 ;                          f11=P11/I11 ;
            f5=f6 ;                             f8=f7-f11 ;
            f9=f8 ;                             f10=f8 ;
           dQ9=f9 ;                             f2=f1-f5 ;
            f3=f2 ;                             f4=f2 ;
            e10=f10*R10 ;                     dQ3=f3 ;
            e4=f4*R4 ;                          e8=e9+e10 ;
            e11=e8 ;                          dP11=e11 ;
            e2=e3+e4 ;                          e5=e2 ;
            e7=e8 ;                             e1=e2 ;
            e6=e5-e7 ;                        dP6=e6 ;
```

This section contains the equations that define the dynamics of the entire system. This section contains the states in derivative form and also contains a single equation for each of the possible outputs.

Derivative Vector

```
% Derivatives vector
p_qdot = [dQ9; dQ3; dP11; dP6] ;
```

This is where the derivative form of the states are all collected into one vector and then sent to the integrating engine.

Sample for Building Desired Output Vectors

```
        % ...  Define output vectors (efforts,flows)...
        % Sample Structure. Add any effort, flow or other variables to be
plotted
        % to the following "EFFORTS" or "FLOWS" vectors
        % Activate in "campgmod.m" suggested structure of graphical output
        %  TIME(STEP,1)=t;                % Define time vector
        %  EFFORTS(STEP,:) = [e5 e11 e4]; % Define efforts vector
        %  FLOWS(STEP,:)   = [f2 f9  f8]; % Define flows vector
        %  STEP=STEP+1;
        %
        % In "campgmod.m" the following structure is included
        % Sample structure for plotting Output Variables as defined in
"campgequ.m"
        %   Example:  If the efforts and flows were defined as:
        %    EFFORTS(STEP,:) = [e5 e11 e4];
        %    FLOWS(STEP,:)   = [f2 f9  f8];
        %  figure(2)
        %  Plot e11 vs TIME (Second column of "EFFORTS" vector)
        %   subplot (211), plot (TIME,EFFORTS(:,2),'b'),grid
        %   title(' Effort variable of vector "EFFORTS(:,2)" stored in column
2')
        %  Plot f8 vs time  (Third column of "FLOWS" vector)
        %   subplot (212), plot (TIME,FLOWS(:,3),'m'),grid
        %   title(' Flow variable of vector "FLOWS(:,3)" stored in column 3')
```

This is where the desired outputs are all collected into vectors. The vectors are created here and they are called set as "global" variables in Matlab. This enables them to be building in this file and then plotted in the CAMPGMOD.M file. The user can enable and the edit these vectors to contain any outputs that they are interested in monitoring or they can leave this alone if they do not need to monitor any outputs.

CAMPGSYM.M

This file is used by itself. It does not require the use of any other file that CAMPG creates. This file is primarily used to determine the transfer functions of the system. It can also be used to solve the system and monitor certain outputs as the combination of the other two files did. But this file can only be used with linear systems.

This example listing is the listing for the linear example that is seen in section 3.7. Nothing will be done with this file in section 3.7. In section 3.8, another system will be interfaced with Matlab and will be used to demonstrate how to get the transfer functions of a system. This is exactly the way the this file would look just after the interfacing with Matlab has been done. As seen here, the sections of the file are very clear and straight forward.

Listing of campgsym.m

```
 %  CAMPG/MATLAB  - Symbolic State Space Model
 %  ...........campgsym.m   CAMPG/MATLAB function ...........
 %  System symbolic matrices, generates transfer functions
   clear
 % ......  Initial conditions  ........
 % Q9IN= ?? ; Q3IN= ?? ;
 % P11IN= ?? ; P6IN= ?? ;
 % initial = [Q9IN; Q3IN; P11IN; P6IN] ;
 % ......System Physical Parameters........
 % global C3 R4 I6 C9 R10 I11
 % Convert system physical parameters and system matrices to
symbols
   syms C3 R4 I6 C9 R10 I11
 % C3 = ?? ; R4 = ?? ;
 % I6 = ?? ; C9 = ?? ;
 % R10 = ?? ; I11 = ?? ;
 % ...... External inputs se(t), sf(t) ......
 % global SF1
 % SF1 = ?? ;
 % State variables vector
 % p_q = [Q9; Q3; P11; P6] ;
 % System Differential Equations-First Order Form
 % Derivatives vector
 % p_qdot = [dQ9; dQ3; dP11; dP6] ;
 %  ... System Differential Equations-State Space form A, B,
C, D symbolic matrices...
 %...Derivatives (dp,dq) and output variables (e,f)...
 %
 %... Generate A, B matrices corresponding to states p'sand
q's     ...
 % dQ9=P6/I6-P11/I11
   A(1,:) = [0,0,-1/I11,1/I6];
   B(1,:) = [0];
 % dQ3=SF1-P6/I6
   A(2,:) = [0,0,0,-1/I6];
   B(2,:) = [1];
 % dP11=Q9/C9+P6/I6*R10-P11/I11*R10
   A(3,:) = [1/C9,0,-1/I11*R10,+1/I6*R10];
   B(3,:) = [0];
 % dP6=Q3/C3+SF1*R4-P6/I6*R4-Q9/C9-P6/I6*R10+P11/I11*R10
   A(4,:) = [-1/C9,1/C3,+1/I11*R10,-1/I6*R4-1/I6*R10];
   B(4,:) = [+1*R4];
 %
 % Generate C and D matrices correspoding to outputs e's and
f's
 % f1=SF1
   % C(#,:) = [0,0,0,0];
   % D(#,:) = [1];
 % e3=Q3/C3
   % C(#,:) = [0,1/C3,0,0];
   % D(#,:) = [0];
 % f6=P6/I6
   % C(#,:) = [0,0,0,1/I6];
   % D(#,:) = [0];
 % f7=P6/I6
   % C(#,:) = [0,0,0,1/I6];
   % D(#,:) = [0];
 % e9=Q9/C9
   % C(#,:) = [1/C9,0,0,0];
   % D(#,:) = [0];
 % f11=P11/I11
   % C(#,:) = [0,0,1/I11,0];
   % D(#,:) = [0];
 % f5=P6/I6
   % C(#,:) = [0,0,0,1/I6];
   % D(#,:) = [0];
 % f8=P6/I6-P11/I11
   % C(#,:) = [0,0,-1/I11,1/I6];
   % D(#,:) = [0];
 % f9=P6/I6-P11/I11
   % C(#,:) = [0,0,-1/I11,1/I6];
   % D(#,:) = [0];
 % f10=P6/I6-P11/I11
   % C(#,:) = [0,0,-1/I11,1/I6];
   % D(#,:) = [0];
 % f2=SF1-P6/I6
   % C(#,:) = [0,0,0,-1/I6];
   % D(#,:) = [1];
 % f3=SF1-P6/I6
   % C(#,:) = [0,0,0,-1/I6];
   % D(#,:) = [1];
 % f4=SF1-P6/I6
   % C(#,:) = [0,0,0,-1/I6];
   % D(#,:) = [1];
 % e10=P6/I6*R10-P11/I11*R10
   % C(#,:) = [0,0,-1/I11*R10,1/I6*R10];
   % D(#,:) = [0];
 % e4=SF1*R4-P6/I6*R4
   % C(#,:) = [0,0,0,-1/I6*R4];
   % D(#,:) = [1*R4];
 % e8=Q9/C9+P6/I6*R10-P11/I11*R10
   % C(#,:) = [1/C9,0,-1/I11*R10,+1/I6*R10];
```

```
   % D(#,:) = [0];
 % e11=Q9/C9+P6/I6*R10-P11/I11*R10
   % C(#,:) = [1/C9,0,-1/I11*R10,+1/I6*R10];
   % D(#,:) = [0];
 % e2=Q3/C3+SF1*R4-P6/I6*R4
   % C(#,:) = [0,1/C3,0,-1/I6*R4];
   % D(#,:) = [+1*R4];
 % e5=Q3/C3+SF1*R4-P6/I6*R4
   % C(#,:) = [0,1/C3,0,-1/I6*R4];
   % D(#,:) = [+1*R4];
 % e7=Q9/C9+P6/I6*R10-P11/I11*R10
   % C(#,:) = [1/C9,0,-1/I11*R10,+1/I6*R10];
   % D(#,:) = [0];
 % e1=Q3/C3+SF1*R4-P6/I6*R4
   % C(#,:) = [0,1/C3,0,-1/I6*R4];
   % D(#,:) = [+1*R4];
 % e6=Q3/C3+SF1*R4-P6/I6*R4-Q9/C9-P6/I6*R10+P11/I11*R10
   % C(#,:) = [-1/C9,1/C3,+1/I11*R10,-1/I6*R4-1/I6*R10];
   % D(#,:) = [+1*R4];
 %
   A
   B
   C
   D
 % Generate vector of transfer functions. Example:
 %     e3(s)/SE1(s),f4(s)/SF10(s),q4(s)/SE1(s)
 % Define SI matrix
   syms s

 %   Find the size of A and then figure out I
   I=eye(4);
 % Use Matlab Symbolic Tool Box to do symbolic matrix
operations leading
 % to the calculation of symbolic transfer functions
 %  ... Transfer Functions Matrix H ...

    H=C*inv(s*I-A)*B +D
    pretty(collect(H))

 %
 % Frequency Response Sample structures
 % [num,den]=H
 % bode(num,den)
 % Frequency Response
 % Bode Plots
 % [num,den]=ss2tf(A,B,C,D,1)
 % bode(num,den)
```

What follows is the same file seen above, but this time the file has been broken down into easier to see sections. Some of the file was excluded from this second listing. This was done because the only parts that are going to be shown here are the parts that the user may have to change.

Converting Physical Parameters to Symbols

```
% Convert system physical parameters and system matrices to symbols
syms C3 R4 I6 C9 R10 I11
```

This section is needed to convert the physical parameters to symbols. This is done so the transfer functions will all be symbolic. The matrices that are created will also be symbolic.

Creating A and B Matrices in Terms of the States

```
      %... Generate A, B matrices corresponding to states
p'sand q's      ...
      % dQ9=P6/I6-P11/I11
      A(1,:) = [0,0,-1/I11,1/I6];
      B(1,:) = [0];
      % dQ3=SF1-P6/I6
      A(2,:) = [0,0,0,-1/I6];
      B(2,:) = [1];
      % dP11=Q9/C9+P6/I6*R10-P11/I11*R10
      A(3,:) = [1/C9,0,-1/I11*R10,+1/I6*R10];
      B(3,:) = [0];
      % dP6=Q3/C3+SF1*R4-P6/I6*R4-Q9/C9-P6/I6*R10+P11/I11*R10
      A(4,:) = [-1/C9,1/C3,+1/I11*R10,-1/I6*R4-1/I6*R10];
      B(4,:) = [+1*R4];
```

This section is the section were the A and B matrices are actually created. The A and B matrices are used in the format:

$$\mathbf{y' = Ax + Bu}$$

Where: "x" is the state vector and "u" is the input vector. The states are the P's and Q's and the inputs are the sources.

Creating C and D Matrices in Terms of the States

```
   % Generate C and D matrices correspoding to outputs e's
and f's
   % f1=SF1
   % C(#,:) = [0,0,0,0];
   % D(#,:) = [1];
   % e3=Q3/C3
   % C(#,:) = [0,1/C3,0,0];
   % D(#,:) = [0];
   % f6=P6/I6
   % C(#,:) = [0,0,0,1/I6];
   % D(#,:) = [0];
   % f7=P6/I6
   % C(#,:) = [0,0,0,1/I6];
   % D(#,:) = [0];
   % e9=Q9/C9
   % C(#,:) = [1/C9,0,0,0];
   % D(#,:) = [0];
   % f11=P11/I11
   % C(#,:) = [0,0,1/I11,0];
   % D(#,:) = [0];
```

This section is where the C and D matrices are created. These matrices are created in the same fashion that the A and B matrices are created, with one exception. These matrices are created by the user and the user decides which outputs to initialize. This is done by removing the "%" from in front of the line that needs to be initialized and then inserting a number in place of "#". The number that is inserted is going to be the row of the matrix that output will occupy. As seen here this is not the entire C and D matrix creation section.

This was done because the entire listing can be seed above under "CAMPGSYM.M Listing".

Creating an Identity Matrix

```
%   Find the size of A and then figure out I
I=eye(4);
```

This is where the identity matrix is created that will be used in the calculation of the transfer functions. This section needs no changes to be made. CAMPG automatically creates this section and sets the size of it equal to the number of states.

Creation of the Transfer Function Matrix

```
%  ... Transfer Functions Matrix H ...
H=C*inv(s*I-A)*B +D
pretty(H)
collect(H)
```

This is where the actual matrix that contains the transfer functions is created and then converted into a format that can be read and understood by the user.

If the user desires, he/she can obtain the transfer functions in numeric format along with the symbolic format that is inherent to this file. To do so some modifications to the file must be made. If the user does not wish to see the transfer functions in symbolic format, they can remove the SYMS command in the beginning of the file and define the variables in terms of their actual values.

If the user wishes to see the symbolic and the numeric format of the transfer functions, this can be done also. To do this, the user needs to redefine the parameters as their actual numeric value and create another set of A, B, C and D matrices, names something else, say AA, BB, CC, DD. .Then the transfer functions need to be generated. But this time they need to be generated twice, once for the symbolic matrices and once for the numeric matrices. An example of this is seen below:

```
      %.......Setting initial conditions...
      Q9IN=0; Q3IN=0; P6IN=16763.96; P11IN=1117.6;

      %Creating Initial Conditions vector to be used for
simulation...
      IC = [Q9IN,Q3IN,P11IN,P6IN];

      %Setting the variables to be used for simulation...
      C3=1/300000;  R4=80000; I6=1500;  C9=1/10000;  R10=500;
I11=100; SF1=0;

      %Creating the vectors to be passed to the S-function for
simulation...
      AA=double(subs(A));
      BB=double(subs(B));
      CC=double(subs(C));
      DD=double(subs(D));

      % Generate vector of transfer functions. Example:
      %    e3(s)/SE1(s),f4(s)/SF10(s),q4(s)/SE1(s)
      % Define SI matrix
      syms s

      %  Find the size of A and then figure out I
      I=eye(4);

      % Use Matlab Symbolic Tool Box to do symbolic matrix
        operations leading
      % to the calculation of symbolic transfer functions
      %  ... Transfer Functions Matrix H ...

      H=C*inv(s*I-A)*B +D
      pretty(collect(H))

      HH=CC*inv(s*I-AA)*BB +DD
      pretty(HH)
      collect(HH))
```

The above information on how to create real matrices from the symbolic matrices could be used in conjunction with Simulink to model the system. Using this file with Simulink could be an alternative method to modeling the system as opposed to the method discussed in section 3.7. Using the AA, BB, CC, and DD matrices that are real matrices in Simulink would produce the same results that are produced in section 3.7. This will be discussed in Section 3.9.

3.4 Useful Runtime Commands used with CAMPG/MATLAB

Matlab has an entire suite of commands that are built in. Many of these are very useful in getting the data that is desired from the model. Some of the more useful runtime commands are listed below with a short description of each. For a more complete list of Matlab runtime commands and a more detailed description with examples of how to use each command, type "helpdesk" at the Matlab command prompt in the Matlab workspace.

SUBPLOT Used to put multiple plots on the same graph

PLOT Used to plot the values in the vector called "Y" against the values in the vector called "X". These vectors need to be the same length. These vectors can be called anything.

FPRINTF Used to display numbers or strings in a formatted style.

DISP Used to display what ever is enclosed in the single quotes in the brackets.

Usually used to send text messages to the screen.

SYMS Used to declare variables, ie R2, I12, C5, etc…as being symbolic. Good for using when getting transfer functions.

GLOBAL Used to declare a variable as global between the workspace and a function or M-file or between two or more files. Simply make the GLOBAL statement in each file where the variable is to be used and the variable only needs to be defined once.

XLABEL Allows the user to label the x-axis of a graph.

YLABEL Allows the user to label the y-axis of a graph.

TITLE Allows the user to create a title for a graph.

LEGEND Allows the user to create a legend for a graph.

ZOOM Allows the user to set the graph to zoom mode. When a graph is in zoom mode, the user can zoom in on a particular area of the graph to get a better feel for what is going on. Also allows the user to zoom out.

GRID Allows the user to set grid lines on the graph.

CLEAR Allows the user to clear the variables that have been declared. Very useful in the beginning of an M-file. Without this command, the user may be using data that was created during another run of the simulation or during another run of another completely different simulation.

SIZE Used to determine the size of a vector or a matrix.

FORMAT Allows the user to specify the format of the numbers that are to be displayed on the screen. They can be displayed in scientific format, with 4 decimal places, with 8 decimal places, etc.

WHILE Used to start a while loop.

FOR Used to start a for loop

IF Used for conditional features or parameters.

ELSE Used for optional conditions.

END Used to end while, for, if and else statements.

3.5 CAMPG/Matlab Tutorial

The following is a summary of the steps that are to be taken to generate a bond graph model from scratch and end up with the final analysis results in the form of calculated values and plots that will allow the engineer to make design decisions.

1 - GENERATE THE BOND GRAPH - The bond graph model can be created right on the screen or transferred from a model drawn on paper. The Technical References offer detailed explanation of the methods for generating the bond graph models from real dynamic systems.

2 - CAMPG - The bond graph model is entered using the menu and the mouse. This is described in detail later in this document. CAMPG is called by double clicking on the icon as described earlier in section 3.2 and then the user can proceed to draw the bond graph model. CAMPG will point out modeling problems using different colors and allowing the user to examine the system equations as the model is entered. There are clear indicators on the screen as to the status of the cursor and the actions that the program will take. References outline in detail the fundamental principles behind the method.

3 - GENERATE A SET OF USABLE M-FILES - Once the model is completed on the screen and no modeling problems that will prevent the generation of a close form set of equations have been detected, the user will select the "Interface" menu and then choose "Matlab" from the drop down menu that appears. Once this has been done, CAMPG will generate the M-files, campgmod.m, campgequ.m and campsym.m, containing all the necessary initial conditions variables, parameters, time controls and the system differential equations in first order form. This form is completely compatible with a state variable form of the system equations.

4 - ENTER PARAMETER VALUES - CAMPG will place the user in a position to edit the three files that it generated. Now the user needs to enter the values of the initial conditions, time control, physical parameters, nonlinear equations, nonlinear functions, activated bond specifications, signals and any other description necessary to complete the model.

The formatting and sections of these files along with the purposes and uses have been described in detail in the section called section 3.3.

5 - RUN Matlab - The user runs Matlab using the three files created by CAMPG in the manner that is described in the three examples at the end of this chapter. These files were completed in the previous step. These files can be named any other name that the user wants to use as long as all references in the files reflect the name change. Now the user is in a position to enter and take advantage of all the Matlab run time commands. The user can issue commands to simulate, display and plot the calculated values. The SUBPLOT, PLOT, FPRINTF and DISP commands are used for this purpose. Section 3.4 offers more information on this step.

6 - OPTIMIZE SIMULATION - Once familiar with the previous steps and confident to obtain results from Matlab, the user can proceed to optimize and speed up the simulation as well as run several different simulations on the model under study.

Step by Step Explanation

A complete step by step explanation of everything that is required of the user from start to finish is listed in each of the examples at the end of this section. The examples are in sections 3.7, 3.8 and 3.9.

3.6 Linear Example – Vehicle Crash Test – MOD and EQU

In this example, a complete step by step explanation will be given for the entire process from a blank screen in CAMPG to the plotting of the desired outputs and states in Matlab.

PROBLEM:
The dummy in the figure shown below is driving his new VW-Rabbit into a wall!!! Will his shock absorbing bumper (k2,b2) and his seat belts (k1, b1) prevent him from hitting the windshield without breaking his collar bone?

DATA ON INJURIES (SAE Handbook)
Seat belts must be tested to 3000 lbs. (1.334×10^{4}) N
Chest can sustain a force of 1500 lbs distributed over 30 in$^{3.}$
Seat belt effective area = 30 in^{2}
Shoulder strap-seat belt combination = 60 in^{2}

PHYSICAL PARAMETERS

M= 1500 Kg,	k_1= 1 x 10^{4} N/m,	b_1=500 N-s/m
m= 100 kg,	k_2= 3 x 10^{5} N/m,	b_2=8 x 10^{4} N-s/m

Physical System of Dummy in Car

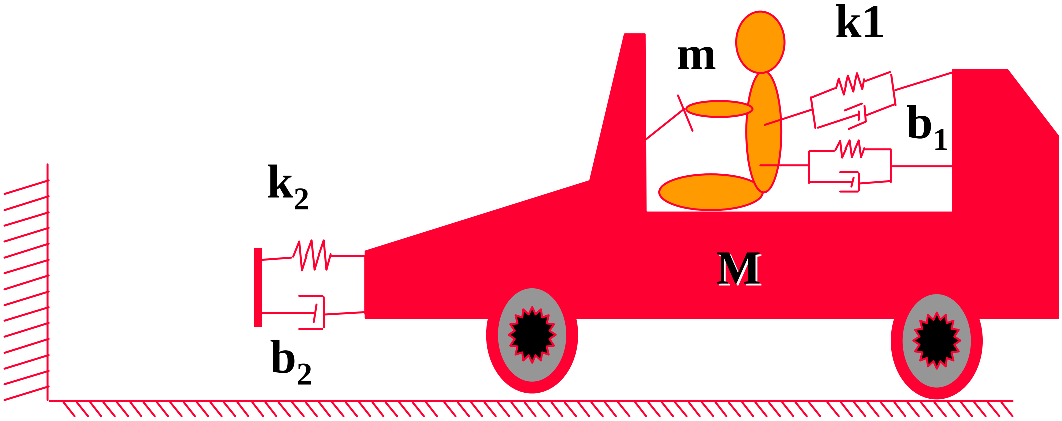


Fig. 3-6 Seat belt design dynamic model

OBJECTIVES:

1. Generate an engineering model of a physical system.

2. Transform the engineering model of reality into a computer model for simulation using the Computer Aided Modeling Program (CAMPG).

2. Perform interactive simulation and generate numerical and graphical output using Matlab.

4. Interpret the results, make design decisions and perform simulation of several models in an interactive way.

PROCEDURE FOR SOLUTION

1. Construct an engineering model of the crash test and consider only the time when the bumper is in contact with the wall. *Fig. 3-6* shows the engineering model of the crash test.

2. Generate a bond graph model. A bond graph model for this system is seen in *Fig. 3-7*.

3. Enter the Bond Graph description into the CAMPG program. *Fig. 3-8* shows the CAMPG screen that was generated after entering the bond graph model.

Bond Graph Model

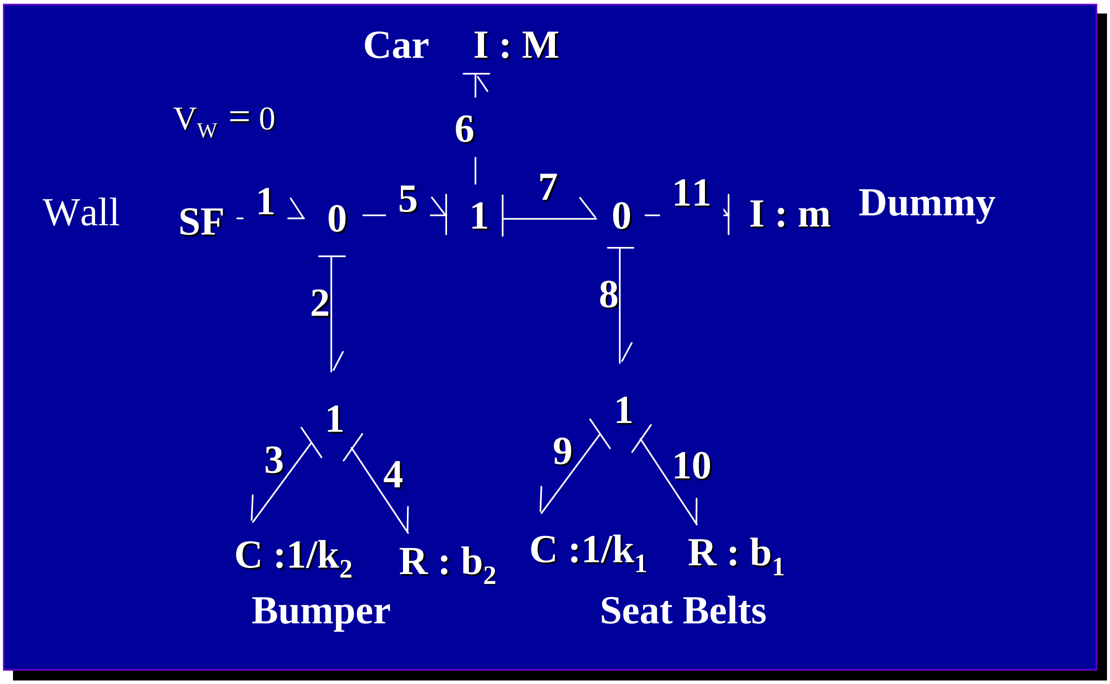
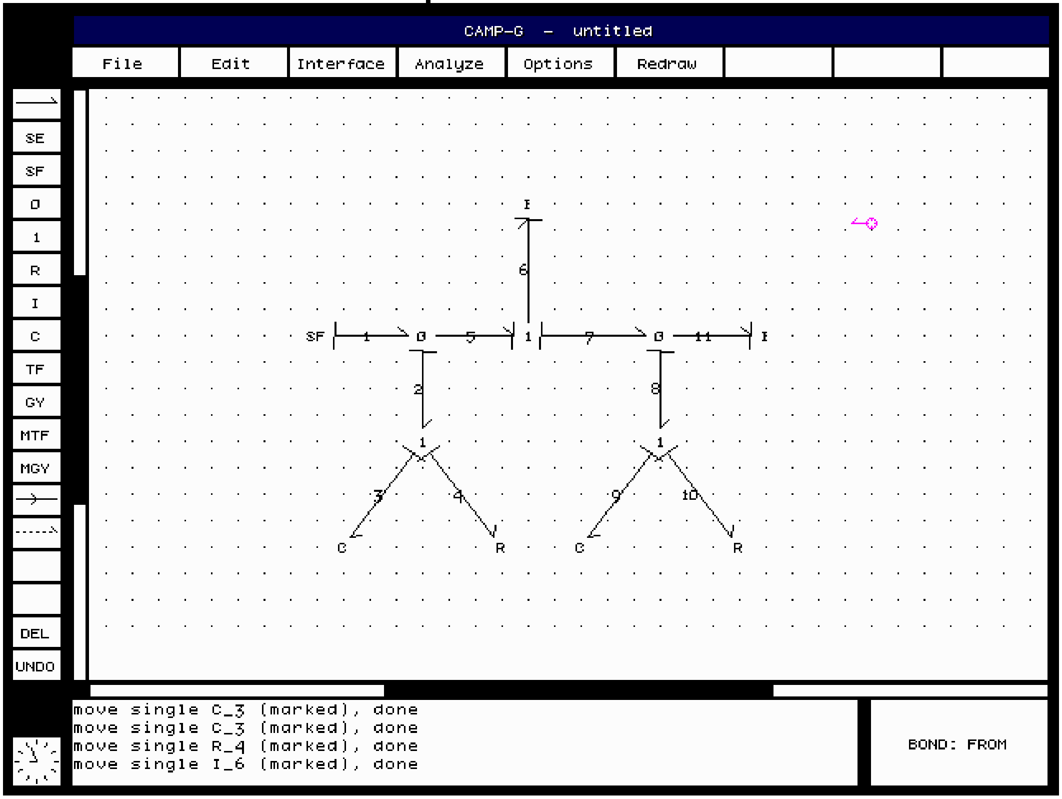


Fig. 3-7 Crash test bond graph model

Bond Graph as Created in CAMPG



```
move single C_3 (marked), done
move single C_3 (marked), done
move single R_4 (marked), done
move single I_6 (marked), done
```

Fig 3-8 Bond Graph completed in CAMPG

The SYSTEMATIC method was used to enter the bond graph model shown in *Fig. 3-8.* Below is a detailed description how this was done. The symbol (CUR) means to select with the cursor. The symbol <CR> means to enter from the keyboard.
****

CAMPG <CR> This brings up the CAMPG screen with a logo. Any movement of the mouse or typing any character, will clear the logo and show a

		blank screen or will bring up the latest model generated and stored in the SESSION.BG file.
EDIT	(CUR)	These next three steps clear the screen if there is an existing session file. If there is no previous SESSION.BG file, these steps are not necessary.
DELETE	(CUR)	
ALL	(CUR)	
YES	(CUR)	
OPTIONS	(CUR)	This pull-down menu selection will be used to turn on the STICKY function so that all the similar elements can be placed all at once. This step allows the SYSTEMATIC METHOD of building the bond graph model.
STICKY	(CUR)	
-ON-	(CUR)	
1	(CUR)	Select the (1) from the menu on the left to place the ONE JUNCTIONS.
	(CUR)	Move the cursor and click in the middle of the screen.
	(CUR)	Move the cursor 4 grids to the right and 4 grids down and click again to place the second (1).
	(CUR)	Move the cursor 8 grids to the left and click to put the third (1) on the screen.

0 (CUR) Select the (0) from the left hand menu to place the ZERO JUNCTIONS on the screen.

(CUR) Click the cursor at 4 grids to the left of the (1) (middle of screen) and at 4 grids to the right of it.

C (CUR) Select C from the menu in order to place the capacitive elements (C) on the Bond graph.

(CUR) Place one of the (C) elements 2 grids below and 2 grids to the left of the (1) element on the left then move 8 grids to the right and place the other.

R (CUR) Select the resistive elements (R) from the left hand menu.

(CUR) Place these (R) elements 4 grids to the right of each (C) element.

I (CUR) Select the (I) element from the left menu.

(CUR) Place the two inertia elements (I) 4 grids above the central (1) and 4 grids to the right of the right most (0).

SF (CUR) Select the FLOW SOURCE from the menu on the left.

(CUR) Place this (SF) 4 grids to the left of the left most (0).

(bond symbol)(CUR) Select the BOND SYMBOL (top box in the left hand menu) to join all of the elements with bonds.

SF (screen) (CUR) Click on the (SF) on the screen.

0 (screen) (CUR) Click on the closest (0) on the screen.

0 (screen) (CUR) Click on the same (0).

1 (screen) (CUR) Click on the lower left (1) on the screen. There should be now have 2 bonds on the screen. Continue this process until the rest of the bonds have been created.

Notice that some of the bonds are red just after they are placed. This means that the system detects an error in the bond graph construction. These errors while the bond graph is being assembled are simply warnings to the user that the bond graph is not a close form system but rather some bonds are not complete yet. They also tell the user that the causality can not be completed up to that point. If these errors continue after completion of the bond graph, it means that there are loops, derivative causality or incomplete bonds that will prevent the generation of a close form system of equations. The user needs to investigate and correct it.

The errors can be determined by inspection of the bond graph or with assistance from CAMPG. Click on ANALYZE, then EXPLAIN and then once again on the red bond or element. The DIALOGUE BOX will provide an explanation of the error. Most likely, the error will disappear after the bond graph has been completed. This feature is excellent to assist in defining correct bond graph models.

The user has now completed the bond graph model. You can look at the equations using ANALYZE and PEEK. This can be done by selecting PEEK under the ANALYZE button; the cursor will change to the "eye".

Click the mouse on any element, junction or bond. The equations for that junction, bond or the constitutive relations of the physical elements will be displayed. Once the bond graph is completed, CAMPG is ready to process the model to generate the Matlab files discussed earlier in section 3.3.

This example showed how to use the STICKY feature and the SYSTEMATIC METHOD. The bond graph could also have been created by the SEQUENTIAL METHOD. This means connecting the elements immediately after they were placed on the screen instead of at the end. The elements and bond are laid out sequentially. Both of these methods create the same end product and the relative efficiency of each depends on the type of bond graph being constructed and the ability of the user to use the most familiar method for that person.

INTERFACE (CUR)	From this menu the user can select the simulation language, go back to DOS or Windows and saves the current model on the screen in a file named SESSION.BG.
MATLAB (CUR)	Select to generate the Matlab model and simulation files.

4. CAMPG generates a computer model description and writes the files CAMPGMOD.M, CAMPGEQU.M and CAMPGSYM.M. Only CAMPGMOD.M and CAMPGEQU.M files are shown below. Section 3.8 uses the CAMPGSYM.M file, see that section for a complete example of using that file. These files have been edited to include the values of the physical parameters initial conditions and external inputs. To see the files as Matlab creates them, see section 3.3.

Listing of CAMPGMOD.M

```
%     CAMPG/MATLAB - GENERATED MODEL DESCRIPTION:
%       The following files have been generated
```

```
 %      campgmod.m  => m file containing model parameters
 %                    intial conditions, sources and
simulation controls
 %      campgequ.m  => m function containing the system
 %                    first order differential equations
 %      campgsym.m  => m file containing system matrices in
symbolic form
 %
 %    For simulation and control, edit these files
 %     Enter values for physical parameters, initial
 %     conditions,inputs and time controls
 %     in places where the ?? marks appear
 %     Standard generalized variables in Bond Graph notation
used.
 %
 %......CAMPGMOD.M - MATLAB MODEL INPUT FILE  ......
   clear
 % ......  Initial conditions  ........
             Q9IN= 0 ; Q3IN= 0 ;
             P11IN= 1117.6 ; P6IN= 16763.96 ;
   initial = [Q9IN; Q3IN; P11IN; P6IN] ;
 % ......System Physical Parameters........
   global C3 R4 I6 C9 R10 I11
             C3 = 1/300000 ;  R4 = 80000 ;
             I6 = 1500 ;  C9 = 1/10000 ;
             R10 = 500 ;  I11 = 100 ;
 % ...... External inputs se(t), sf(t) ......
   global SF1
             SF1 = 0 ;
 %..... Simulation Time Control .....
             t0= 0 ;   %  Initial Time
             tf= 1 ;   %  Final Time
             tspan= [t0 tf];
 %.....  Define Outputs .....
   global TIME STEP EFFORTS FLOWS
   STEP=1;
 % ......  Computer Simulation ......
 %  Solution of system equations using Matlab "ode23 or ode45"
function
 %  The "campgequ.m" function contains the system differential
 %  equations in state variable form.
 %
 %  It returns the vector [t,p-q] where:
 %   t = time and p-q = vector of state variables
 %   [t,p_q] is a column vector with rows [t, p_q(1) p_q(2)
p_q(3) ...]
   [t,p_q] = ode23('campgequ',tspan,initial);
 %          Q9= p_q(1) ; %          Q3= p_q(2) ;
 %          P11= p_q(3) ; %          P6= p_q(4) ;
 % State variables vector
 % p_q = [Q9; Q3; P11; P6] ;
 %
 % Sample Matlab structure for plotting simulation results
(state variables)
   figure(1)
   plot(t,p_q(:,1),'r'),grid
   title('Distance the Dummy''s head travels')
   ylabel ('Distance (meters)'),xlabel('Time (seconds)')
 %  subplot (212),plot(t,p_q(:,2),'m'),grid
 %  title(' variable p_q(:,2) (stored in column 2), color
magenta')
 %  ylabel ('p_q(2) (units)'),xlabel('Time (seconds)')
 %
 % Sample structure for plotting Output Variables as defined
in "campgequ.m"
 %   Example:  If the efforts and flows were defined as:
 %    EFFORTS(STEP,:) = [e5 e11 e4];
 %    FLOWS(STEP,:)      = [f2 f9  f8];
   figure(2)
 %  Plot e11 vs TIME (Second column of "EFFORTS" vector)
   plot (TIME,EFFORTS,'r'),grid
   title('Force Acting on the Dummy')
   ylabel('Force (N)'), xlabel('Time (seconds)')
 %  Plot f8 vs time  (Third column of "FLOWS" vector)
 %   subplot (212), plot (TIME,FLOWS(:,3),'m'),grid
 %   title(' Flow variable of vector "FLOWS(:,3)" stored in
column 3')
```

```
            %..........BOND GRAPH NOTATION.............
          %  GENERALIZED VARIABLES BOND GRAPH NOTATION :
%-----------------------------------------------------------------------
%                      MECHANICAL         ELECTRICAL    HYDRAULIC
%              | TRANSLATION| ROTATION   |            |
%--------------|------------|------------|------------|----------------
%E (Effort)    |Force       |Torque      |Voltage     |Pressure
%F (Flow)      |Velocity    |Ang Vel.    |Current     |Volume Flow Rate
%Q (Gen Disp)  |Displacement|Angle       |Charge      |Volume
%P (Gen Momentum)|Momentum  |Ang.Moment.|Flux Linkage|Pressure Moment.
%-----------------------------------------------------------------------
% TF (M) (Transformer Modulus)      SE Source Effort
% GY (R) (Gyrator Modulus)          SF Source Flow
```

```
 %--------------------------------------------------------
```

Listing of CAMPGEQU.M

```
   function p_qdot = campgequ(t,p_q)
 %  ...........campgequ.m   CAMPG/MATLAB function ...........
 %  System differential equations, state Vectors
 %
   global C3 R4 I6 C9 R10 I11
   global SF1
   global TIME STEP EFFORTS FLOWS
 % System Differential Equations-First Order Form
 %...... Define State Variables ......
         Q9= p_q(1) ;         Q3= p_q(2) ;
         P11= p_q(3) ;         P6= p_q(4) ;
 % State variables vector
 % p_q = [Q9; Q3; P11; P6] ;
 %...... Define derivatives (dp,dq) and output variables (e,f)
......
         f1=SF1 ;                            e3=Q3/C3 ;
         f6=P6/I6 ;                          f7=f6 ;
         e9=Q9/C9 ;                          f11=P11/I11 ;
         f5=f6 ;                             f8=f7-f11 ;
         f9=f8 ;                             f10=f8 ;
       dQ9=f9 ;                              f2=f1-f5 ;
         f3=f2 ;                             f4=f2 ;
         e10=f10*R10 ;                     dQ3=f3 ;
         e4=f4*R4 ;                          e8=e9+e10 ;
         e11=e8 ;                          dP11=e11 ;
         e2=e3+e4 ;                          e5=e2 ;
         e7=e8 ;                             e1=e2 ;
         e6=e5-e7 ;                        dP6=e6 ;

 % ... Build vector of derivatives p_qdot(n)...
 %        p_qdot1) = dQ9 ; %        p_qdot2) = dQ3 ;
 %        p_qdot3) = dP11 ; %        p_qdot4) = dP6 ;
 % Derivatives vector
   p_qdot = [dQ9; dQ3; dP11; dP6] ;

 % ...  Define output vectors (efforts,flows)...
 % Sample Structure. Add any effort, flow or other variables
to be plotted
 % to the following "EFFORTS" or "FLOWS" vectors
 % Activate in "campgmod.m" suggested structure of graphical
output
   TIME(STEP,1)=t;                % Define time vector
   EFFORTS(STEP,:) = [e11]; % Define efforts vector
 %  FLOWS(STEP,:)   = [f2 f9  f8]; % Define flows vector
   STEP=STEP+1;
 %
 % In "campgmod.m" the following structure is included
 % Sample structure for plotting Output Variables as defined
in "campgequ.m"
 %   Example:  If the efforts and flows were defined as:
 %    EFFORTS(STEP,:) = [e5 e11 e4];
 %    FLOWS(STEP,:)   = [f2 f9  f8];
 %  figure(2)
 %  Plot e11 vs TIME (Second column of "EFFORTS" vector)
 %   subplot (211), plot (TIME,EFFORTS(:,2),'b'),grid
 %   title(' Effort variable of vector "EFFORTS(:,2)" stored
in column 2')
 %  Plot f8 vs time  (Third column of "FLOWS" vector)
 %   subplot (212), plot (TIME,FLOWS(:,3),'m'),grid
 %   title(' Flow variable of vector "FLOWS(:,3)" stored in
column 3')
```

The causality and power flow can be verified since CAMPG will generate the bond graph causality and power flow tables shown below in the CAMPGMOD.M file. These can stay in the file since they do not interfere with the function of the file since they are remarked out.

```
       %*********************    ********************
            %....... BOND GRAPH ANALYSIS .......

 %SYSTEM  DESCRIPTION:


% POWER FLOW:
% BOND    FROM                            TO
% ----    ----                            --
%   1   SF_1                            0_1_2_5
%   2   0_1_2_5                         1_2_3_4
%   3   1_2_3_4                         C_3
%   4   1_2_3_4                         R_4
%   5   0_1_2_5                         1_5_6_7
%   6   1_5_6_7                         I_6
%   7   1_5_6_7                         0_7_8_11
%   8   0_7_8_11                        1_8_9_10
%   9   1_8_9_10                         C_9
%  10   1_8_9_10                         R_10
%  11   0_7_8_11                         I_11

% CAUSALITY FLOW:

% NOTE:  FROM -----| TO

% BOND    FROM                             TO
% ----    ----                             --
%   1   0_1_2_5                          SF_1
%   2   1_2_3_4                          0_1_2_5
%   3   C_3                              1_2_3_4
%   4   R_4                              1_2_3_4
%   5   0_1_2_5                          1_5_6_7
%   6   1_5_6_7                          I_6
%   7   0_7_8_11                         1_5_6_7
%   8   1_8_9_10                         0_7_8_11
%   9   C_9                              1_8_9_10
%  10   R_10                             1_8_9_10
%  11   0_7_8_11                         I_11


% End of model
```

5. Run the files in Matlab. This is done by issuing the following command at the Matlab command prompt:

   CAMPGMOD

6. The following lines were used to generate the output in the form of plots. Sample output plots can be seen at the end of this section with the results.

```
figure(1)
plot(t,p_q(:,1),'r'),grid
title('Distance the Dummy''s head travels')
ylabel ('Distance (meters)'),xlabel('Time (seconds)')
```

DESIGN CRITERIA

The simulation must produce a design of the seat belts and the bumper so that it satisfies the following conditions:

1 He doesn't hit the windshield if he travels at 25 and at 55 mph.

2. What is the force acting on his chest and waist at 25 mph and at 55 mph. Compare the data on injuries and determine if chest or internal injury occurs if: (1) he wears a seat belt only; (2) he wears a seat belt and a shoulder strap.

3. What is the "critical" maximum velocity (when he is safe) at which impact occurs? Hitting the windshield, chest injury, internal injury, seat belt failure, strap failure all should not occur.

4. If he travels without a seat belt. How long does it take for him to hit the windshield at 25 mph, 40 mph, and 55 mph? What is the force acting on him on impact at 25 mph, 40 mph, and 55 mph?

RESULTS

The results obtained from the simulation can be obtained in the form of numerical values or in the form of plots of variables as a function of time. Several designs with different kind of bumpers and shock absorbers were tried. These simulations allow the user to make an optimum decision to satisfy the design requirements. The user is able at this point to decide which is the best design and why. One can perform as many simulations as the user thinks are necessary. In this case it was found from *Fig. 3-9* that at 25 mph the dummy did not hit his head on the windshield. Its maximum displacement was 0.81m. Less than the 1.00 m allowed. It was found from *Fig. 3-10* that the force acting on his body was 9,310 newtons. However this is enough to produce chest injury. The maximum limit allowed is 6,688 newtons. No failure of the seat belts occurs since they can resist a load of 13,340 newtons.

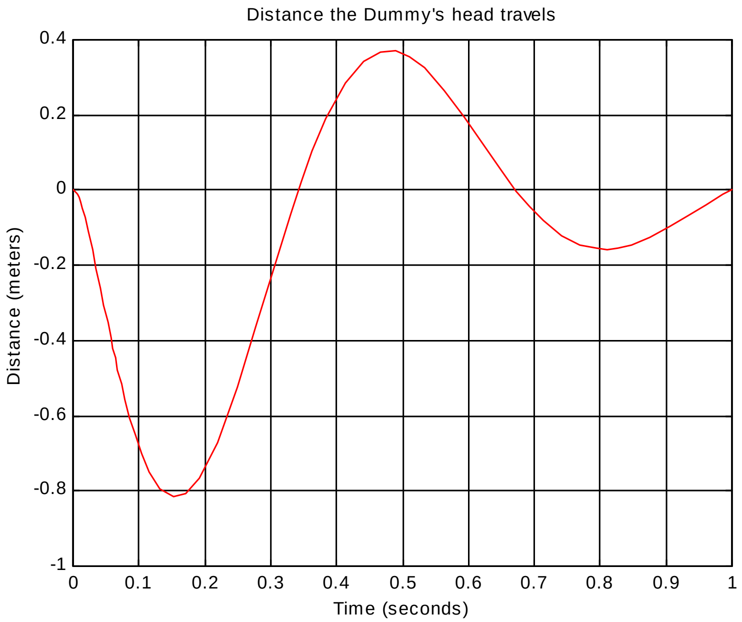


Fig 3-9 Head Displacement

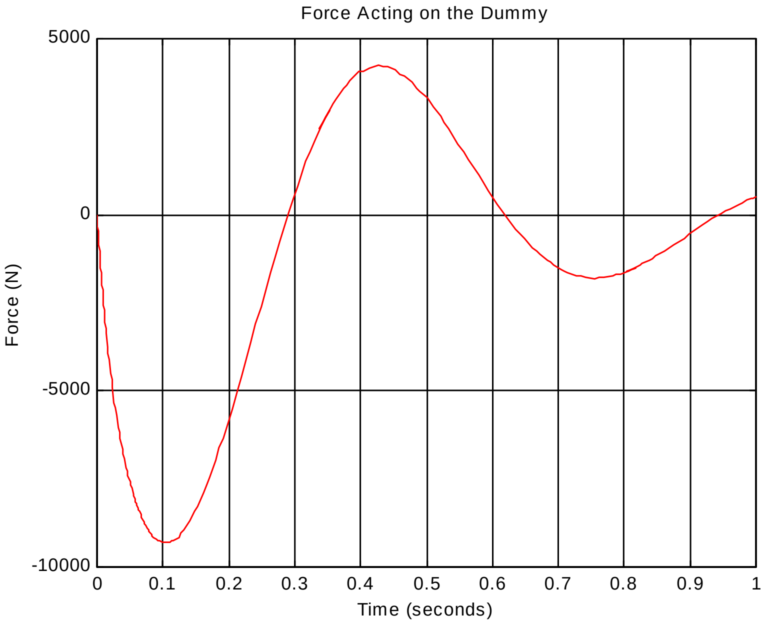


Fig 3-10 Force acting on the dummy

The table shown below, *Table 1*, illustrates the results of the different simulations considering different velocities and physical parameters.

INITIAL	N OF	BUMPER		SEAT BELTS		DUMMY	
VELOCITY	BELTS	K2	B2	K1	B1	E11	Q9
		[N/m]	[N-s/m]	[N/m]	[N-s/m]	[N]	[m]
25	1	300,000	80,000	10,000	500	9,310	0.8167
25	2	300,000	80,000	20,000	1,000	13,147	0.5144
55	1	300,000	80,000	10,000	500	20,483	1.7968
55	2	300,000	80,000	20,000	1,000	29,035	1.1300
55	1	300,000	80,000	10,000	1,000	25,547	1.3780
55	1	300,000	80,000	10,000	1,500	26,714	1.1100
55	1	300,000	80,000	8,000	1,500	25,990	1.1670
55	1	300,000	80,000	5,000	3,000	36,639	0.7500
55	2	300,000	50,000	5,000	3,000	31,184	0.7810
55	2	300,000	10,000	5,000	3,000	25,426	1.0360
55	2	100,000	10,000	5,000	3,000	15,986	0.8580
55	2	50,000	10,000	5,000	3,000	13,129	0.7440

Table 3-1 Simulation Results

The impact at 55 mph is shown in the table above. The displacement of the dummy is 1.79m so he hits the windshield in 0.065 sec. Chest injury also occurs at 20,483 newtons. The values of the shock absorbers can be changed in the bumper and in the seat belts. The dummy hits the windshield in about .1 sec at 25 mph but in just 0.05 sec at 55 mph without a seat belt.

This example illustrates the whole process of modeling and simulation using CAMPG/Matlab for linear systems. The next section will explore the same example but this time using the CAMPGSYM.M file.

3.7 Linear Example – Vehicle Crash Test – CAMPGSYM and Simulink

Every thing that was just done in section 3.7 will be repeated here except this time the CAMPGSYM.M file will be used in conjunction with Simulink, in place of the other files. The entire procedure from above will be repeated for the users benefit.

PROBLEM:
The dummy in the figure shown below, is driving his new VW-Rabbit into a wall!!! Will his shock absorbing bumper (k2,b2) and his seat belts (k1, b1) prevent him from hitting the windshield without breaking his collar bone?

DATA ON INJURIES (SAE Handbook)
Seat belts must be tested to 3000 lbs. (1.334×10^4) N
Chest can sustain a force of 1500 lbs distributed over 30 in^2.
Seat belt effective area = 30 in^2
Shoulder strap-seat belt combination = 60 in^2

PHYSICAL PARAMETERS
M= 1500 Kg, k_1= 1×10^4 N/m, b_1=500 N-s/m
m= 100 kg, k_2= 3×10^5 N/m, b_2=8×10^4 N-s/m

OBJECTIVES:

1. Generate an engineering model of a physical system.

2. Transform the engineering model of reality into a computer model for simulation using the Computer Aided Modeling Program (CAMPG).

3. Perform interactive simulation and generate numerical and graphical output using Matlab.

4. Interpret the results, make design decisions and perform simulation of several models in an interactive way .

PROCEDURE FOR SOLUTION

1. Construct an engineering model of the crash test and consider only the time when the bumper is in contact with the wall. *Fig. 3-6* shows the engineering model of the crash test as well as its corresponding bond graph.

2. Generate a bond graph model. *Fig. 3-7* shows step by step the process of generating the Bond Graph model of the crash test.

3. Enter the Bond Graph description into the CAMPG program. *Fig.3-8* shows the CAMPG screen that was generated after entering the bond graph model.

The SYSTEMATIC method was used to enter the bond graph model shown in *Fig. 3-8.* Below is a detailed description how this was done. The symbol (CUR) means to select with the cursor. The symbol <CR> means to enter from the keyboard.
****

CAMPG <CR> This brings up the CAMPG screen with a logo. Any movement of the mouse or typing any character, will clear the logo and show a blank screen or will bring up the latest model generated and stored in the SESSION.BG file.

EDIT (CUR) These next three steps clear the screen if there is an existing session file. If there is no previous SESSION.BG file, these steps are not necessary.

DELETE (CUR)

ALL (CUR)

YES (CUR)

OPTIONS (CUR) This pull-down menu selection will be used to turn on the STICKY function so that all the similar elements can be placed all at once. This step allows the SYSTEMATIC METHOD of building the bond graph model.

STICKY (CUR)

-ON- (CUR)

1 (CUR) Select the (1) from the menu on the left to place the ONE JUNCTIONS.

(CUR) Move the cursor and click in the middle of the screen.

(CUR) Move the cursor 4 grids to the right and 4 grids down and click again to place the second (1).

(CUR) Move the cursor 8 grids to the left and click to put the third (1) on the screen.

0 (CUR) Select the (0) from the left hand menu to place the ZERO JUNCTIONS on the screen.

(CUR) Click the cursor at 4 grids to the left of the (1) (middle of screen) and at 4 grids to the right of it.

C (CUR) Select C from the menu in order to place the capacitive elements (C) on the Bond graph.

(CUR) Place one of the (C) elements 2 grids below and 2 grids to the left of the (1) element on the left then move 8 grids to the right and place the other.

R (CUR) Select the resistive elements (R) from the left hand menu.

(CUR) Place these (R) elements 4 grids to the right of each (C) element.

I (CUR) Select the (I) element from the left menu.

(CUR) Place the two inertia elements (I) 4 grids above the central (1) and 4 grids to the right of the right most (0).

SF (CUR) Select the FLOW SOURCE from the menu on the left.

(CUR) Place this (SF) 4 grids to the left of the left most (0).

(bond symbol)(CUR) Select the BOND SYMBOL (top box in the left hand menu) to join all of the elements with bonds.

SF (screen) (CUR) Click on the (SF) on the screen.

0	(screen)	(CUR)	Click on the closest (0) on the screen.
0	(screen)	(CUR)	Click on the same (0).
1	(screen)	(CUR)	Click on the lower left (1) on the screen. There should be now have 2 bonds on the screen. Continue this process until the rest of the bonds have been created.

Notice that some of the bonds are red just after they are placed. This means that the system detects an error in the bond graph construction. These errors while the bond graph is being assembled are simply warnings to the user that the bond graph is not a close form system but rather some bonds are not complete yet. They also tell the user that the causality can not be completed up to that point. If these errors continue after completion of the bond graph, it means that there are loops, derivative causality or incomplete bonds that will prevent the generation of a close form system of equations. The user needs to investigate and correct it.

The errors can be determined by inspection of the bond graph or with assistance from CAMPG. Click on ANALYZE, then EXPLAIN and then once again on the red bond or element. The DIALOGUE BOX will provide an explanation of the error. Most likely, the error will disappear after the bond graph has been completed. This feature is excellent to assist in defining correct bond graph models.

The user has now completed the bond graph model. You can look at the equations using ANALYZE and PEEK. This can be done by selecting PEEK under the ANALYZE button; the cursor will change to the "eye". Click the mouse on any element, junction or bond. The equations for that junction, bond or the constitutive relations of the physical elements will be displayed. Once the bond graph is completed, CAMPG is ready to process the model to generate the Matlab files discussed earlier in section 3.3.

This example showed how to use the STICKY feature and the SYSTEMATIC METHOD. The bond graph could also have been created by the SEQUENTIAL METHOD. This means connecting the elements immediately after they were placed on the screen instead of at the end. The elements and bond are laid out sequentially. Both of these methods create the same end product and the relative efficiency of each depends on the type of bond graph being constructed and the ability of the user to use the most familiar method for that person.

INTERFACE (CUR) From this menu the user can select the simulation language, go back to DOS or Windows and saves the current model on the screen in a file named SESSION.BG.

MATLAB (CUR) Select to generate the Matlab model and simulation files.

4. CAMPG generates a computer model description and writes the files CAMPGMOD.M, CAMPGEQU.M and CAMPGSYM.M. Only the CAMPGSYM.M file is shown below. Section 3.7 uses the CAMPGMOD.M and CAMPGEQU.M files, see that section for a complete example of using those files. This file has been edited to include the values of the physical parameters initial conditions and external inputs. Since in this example, the transfer functions are not required, that section of the file has been remarked out. To see this file as Matlab creates it, see section 3.3.

Listing of CAMPGSYM.M

```
%  CAMPG/MATLAB  - Symbolic State Space Model
%  ...........campgsym.m   CAMPG/MATLAB function ...........
%  System symbolic matrices, generates transfer functions
  clear
% ......  Initial conditions  ........
```

```
 % Q9IN= ?? ; Q3IN= ?? ;
 % P11IN= ?? ; P6IN= ?? ;
 % initial = [Q9IN; Q3IN; P11IN; P6IN] ;
 % ......System Physical Parameters........
 % global C3 R4 I6 C9 R10 I11
   global AA BB CC DD IC
 % Convert system physical parameters and system matrices to
symbols
   syms C3 R4 I6 C9 R10 I11 B
 % C3 = ?? ; R4 = ?? ;
 % I6 = ?? ; C9 = ?? ;
 % R10 = ?? ; I11 = ?? ;
 % ...... External inputs se(t), sf(t) ......
 % global SF1
 % SF1 = ?? ;
 % State variables vector
 % p_q = [Q9; Q3; P11; P6] ;
 % System Differential Equations-First Order Form
 % Derivatives vector
 % p_qdot = [dQ9; dQ3; dP11; dP6] ;
 %  ... System Differential Equations-State Space form A, B,
C, D symbolic matrices...
 %...Derivatives (dp,dq) and output variables (e,f)...
 %
 %... Generate A, B matrices corresponding to states p'sand
q's     ...
 % dQ9=P6/I6-P11/I11
   A(1,:) = [0,0,-1/I11,1/I6];
   B(1,:) = [0];
 % dQ3=SF1-P6/I6
   A(2,:) = [0,0,0,-1/I6];
   B(2,:) = [1];
 % dP11=Q9/C9+P6/I6*R10-P11/I11*R10
   A(3,:) = [1/C9,0,-1/I11*R10,+1/I6*R10];
   B(3,:) = [0];
 % dP6=Q3/C3+SF1*R4-P6/I6*R4-Q9/C9-P6/I6*R10+P11/I11*R10
   A(4,:) = [-1/C9,1/C3,+1/I11*R10,-1/I6*R4-1/I6*R10];
   B(4,:) = [+1*R4];
 %
 % Generate C and D matrices correspoding to outputs e's and
f's
 % f1=SF1
   % C(#,:) = [0,0,0,0];
   % D(#,:) = [1];
 % e3=Q3/C3
   % C(#,:) = [0,1/C3,0,0];
   % D(#,:) = [0];
 % f6=P6/I6
   % C(#,:) = [0,0,0,1/I6];
   % D(#,:) = [0];
 % f7=P6/I6
   % C(#,:) = [0,0,0,1/I6];
   % D(#,:) = [0];
 % e9=Q9/C9
    C(2,:) = [1/C9,0,0,0];
    D(2,:) = [0];
 % f11=P11/I11
   % C(#,:) = [0,0,1/I11,0];
   % D(#,:) = [0];
 % f5=P6/I6
   % C(#,:) = [0,0,0,1/I6];
   % D(#,:) = [0];
 % f8=P6/I6-P11/I11
   % C(#,:) = [0,0,-1/I11,1/I6];
   % D(#,:) = [0];
 % f9=P6/I6-P11/I11
   % C(#,:) = [0,0,-1/I11,1/I6];
   % D(#,:) = [0];
 % f10=P6/I6-P11/I11
   % C(#,:) = [0,0,-1/I11,1/I6];
   % D(#,:) = [0];
 % f2=SF1-P6/I6
   % C(#,:) = [0,0,0,-1/I6];
   % D(#,:) = [1];
 % f3=SF1-P6/I6
   % C(#,:) = [0,0,0,-1/I6];
   % D(#,:) = [1];
 % f4=SF1-P6/I6
   % C(#,:) = [0,0,0,-1/I6];
   % D(#,:) = [1];
 % e10=P6/I6*R10-P11/I11*R10
   % C(#,:) = [0,0,-1/I11*R10,1/I6*R10];
   % D(#,:) = [0];
 % e4=SF1*R4-P6/I6*R4
   % C(#,:) = [0,0,0,-1/I6*R4];
   % D(#,:) = [1*R4];
 % e8=Q9/C9+P6/I6*R10-P11/I11*R10
   % C(#,:) = [1/C9,0,-1/I11*R10,+1/I6*R10];
```

```
   % D(#,:) = [0];
 % e11=Q9/C9+P6/I6*R10-P11/I11*R10
    C(1,:) = [1/C9,0,-1/I11*R10,+1/I6*R10];
    D(1,:) = [0];
 % e2=Q3/C3+SF1*R4-P6/I6*R4
   % C(#,:) = [0,1/C3,0,-1/I6*R4];
   % D(#,:) = [+1*R4];
 % e5=Q3/C3+SF1*R4-P6/I6*R4
   % C(#,:) = [0,1/C3,0,-1/I6*R4];
   % D(#,:) = [+1*R4];
 % e7=Q9/C9+P6/I6*R10-P11/I11*R10
   % C(#,:) = [1/C9,0,-1/I11*R10,+1/I6*R10];
   % D(#,:) = [0];
 % e1=Q3/C3+SF1*R4-P6/I6*R4
   % C(#,:) = [0,1/C3,0,-1/I6*R4];
   % D(#,:) = [+1*R4];
 % e6=Q3/C3+SF1*R4-P6/I6*R4-Q9/C9-P6/I6*R10+P11/I11*R10
   % C(#,:) = [-1/C9,1/C3,+1/I11*R10,-1/I6*R4-1/I6*R10];
   % D(#,:) = [+1*R4];
 %
   A
   B
   C
   D
 %
 %.......Setting initial conditions...
        Q9IN=0; Q3IN=0; P6IN=16763.96; P11IN=1117.6;

 %Creating Initial Conditions vector to be used for
simulation...
        IC = [Q9IN,Q3IN,P11IN,P6IN];

 %Setting the variables to be used for simulation...
        C3=1/300000;  R4=80000; I6=1500;  C9=1/10000;
R10=500;  I11=100; SF1=0;

 %Creating the vectors to be passed to the S-function for
simulation...
        AA=double(subs(A))
        BB=double(subs(B))
        CC=double(subs(C))
        %DD=double(subs(D))
         DD=D
 %
 % Generate vector of transfer functions. Example:
 %     e3(s)/SE1(s),f4(s)/SF10(s),q4(s)/SE1(s)
 % Define SI matrix
 %  syms s
 %
 %   Find the size of A and then figure out I
 %  I=eye(4);
 % Use Matlab Symbolic Tool Box to do symbolic matrix
operations leading
 % to the calculation of symbolic transfer functions
 %  ... Transfer Functions Matrix H ...
 %
 %   H=C*inv(s*I-A)*B +D
 %   pretty(collect(H))
 %
 %
 % Frequency Response Sample structures
 % [num,den]=H
 % bode(num,den)
 %
 % Frequency Response
 % Bode Plots
 % [num,den]=ss2tf(A,B,C,D,1)
 % bode(num,den)
```

5. Run the file in Matlab. This is done by issuing the following command at the Matlab command prompt:

   CAMPGSYM

5. Create a Simulink model as seen in *Fig. 3-11*.

Simulink Model

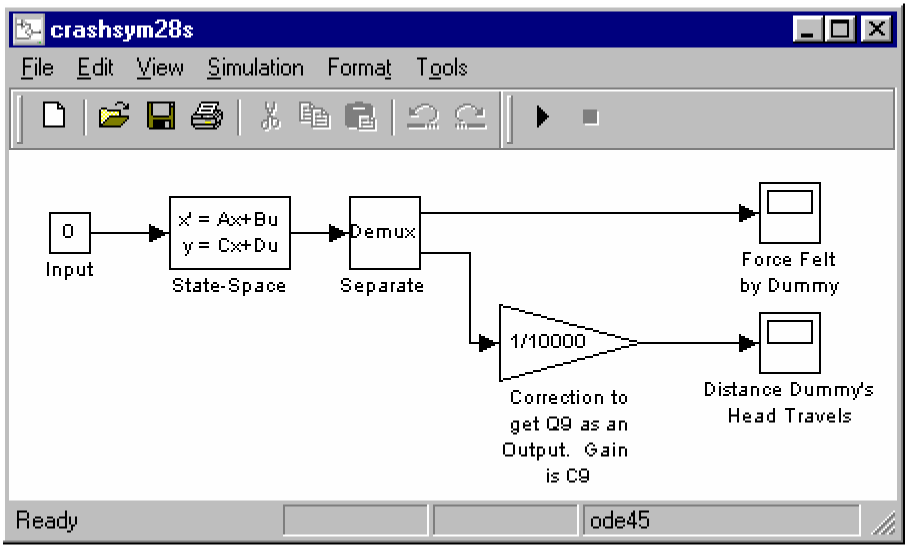
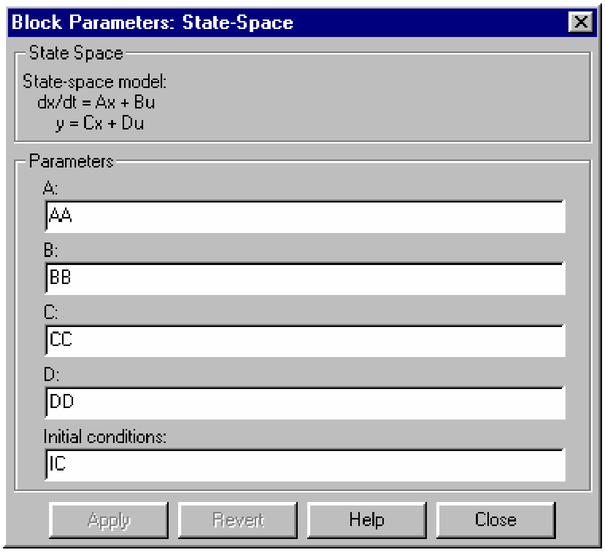


Fig. 3-11 CAMPG/SIMULINK state space model

7. Once the Simulink model has been created, double click on the "State-Space" block to get the input screen to open. See *Fig. 3-12* for this screen. Input the names or the matrices that are to be used Simulink. In this case, they are AA, BB, CC, and DD.



Block Parameters: State-Space

State Space

State-space model:
dx/dt = Ax + Bu
y = Cx + Du

Parameters

A: AA

B: BB

C: CC

D: DD

Initial conditions: IC

Input Window

Fig. 3-12 Matrices Initialization

8. Run the Simulink simulation to get the results. This is done by clicking on the play button that is seen on the Simulink model. See *Fig. 3-11*.

9. Double click on the scopes in the Simulink model, seen in *Fig. 3-11***,** to see the results. See *Fig. 3-13* for the resulting plots as seen on the scopes.

Resulting Plots

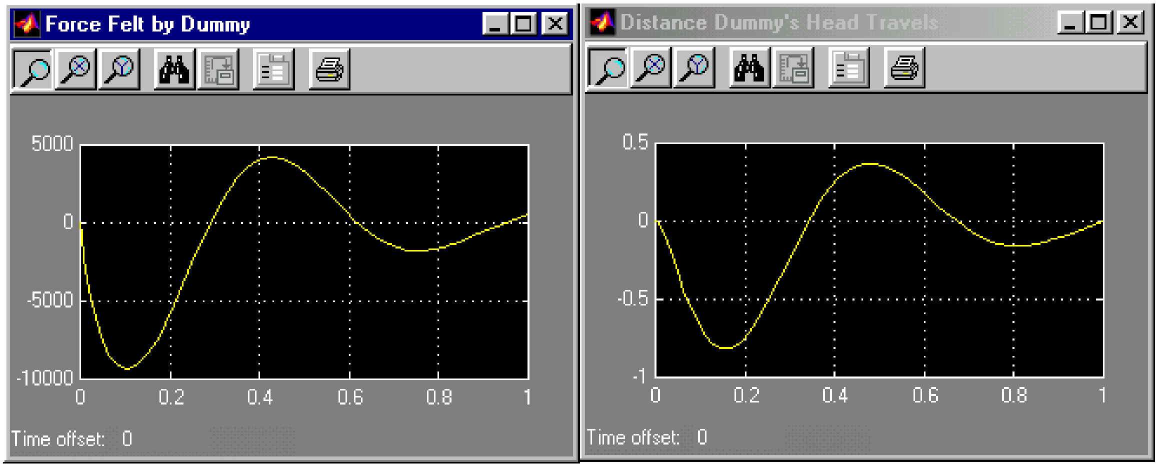


Fig. 3-13 SIMULINK scopes simulation display

DESIGN CRITERIA

The simulation must produce a design of the seat belts and the bumper so that it satisfies the following conditions:

1 He doesn't hit the windshield if he travels at 25 and at 55 mph.

2. What is the force acting on his chest and waist at 25 mph and at 55 mph. Compare the data on injuries and determine if chest or internal injury occurs if: (1) he wears a seat belt only; (2) he wears a seat belt and a shoulder strap.

3. What is the "critical" maximum velocity (when he is safe) at which impact occurs? Hitting the windshield, chest injury, internal injury, seat belt failure, and strap failure should not occur.

4. If he travels without a seat belt. How long does it take for him to hit the windshield at 25 mph, 40 mph, and 55 mph? What is the force acting on him on impact at 25 mph, 40 mph, and 55 mph?

RESULTS

The results obtained from the simulation can be obtained in the form of numerical values or in the form of plots of variables as a function of time. Several designs with different kind of bumpers and shock absorbers were tried. These simulations allow the user to make an optimum decision to satisfy the design requirements. The user is able at this point to decide which is the best design and why. He/She can perform as many simulations as the user thinks are necessary. In this case it was found from the table below that at 25 mph the dummy did not hit his head on the windshield. Its maximum displacement was 0.81m, which is less than the 1.00m allowed. The force acting on his body was 9,310 newtons. However this is enough to produce chest injury. The maximum limit allowed is 6,688 newtons. No failure of the seat belts occurs since they can resist a load of 13,340 newtons.

The table shown below, *Table 2*, illustrates the results of the different simulations considering different velocities and physical parameters.

INITIAL	N OF	BUMPER		SEAT BELTS		DUMMY	
VELOCITY	BELTS	K2	B2	K1	B1	E11	Q9
		[N/m]	[N-s/m]	[N/m]	[N-s/m]	[N]	[m]
25	1	300,000	80,000	10,000	500	9,310	0.8167
25	2	300,000	80,000	20,000	1,000	13,147	0.5144
55	1	300,000	80,000	10,000	500	20,483	1.7968
55	2	300,000	80,000	20,000	1,000	29,035	1.1300
55	1	300,000	80,000	10,000	1,000	25,547	1.3780
55	1	300,000	80,000	10,000	1,500	26,714	1.1100
55	1	300,000	80,000	8,000	1,500	25,990	1.1670
55	1	300,000	80,000	5,000	3,000	36,639	0.7500
55	2	300,000	50,000	5,000	3,000	31,184	0.7810
55	2	300,000	10,000	5,000	3,000	25,426	1.0360
55	2	100,000	10,000	5,000	3,000	15,986	0.8580
55	2	50,000	10,000	5,000	3,000	13,129	0.7440

Table 3-2 Simulation results

The impact at 55 mph is also seen in the table above. The displacement of the dummy is 1.79m so he hits the windshield in 0.065 sec. Chest injury also occurs at 20,483 newtons. The values of the shock absorbers can be changed in the bumper and in the seat belts. The dummy hits the windshield in about .1 sec at 25 mph but in just 0.05 sec at 55 mph without a seat belt.

This example illustrates one use of the CAMPGSYM.M file. The next section will demonstrate how to obtain transfer functions with the CAMPGSYM.M file.

3.8 Obtaining Transfer Functions Example – Multienergy System Example

Bond Graph modeling is the appropriate method when systems have components in different energy domains but they act as a complete dynamic system. One of the most classic ones is the model of a DC motor. This is an electromechanical system. It was deliberately chosen because keeping continuity with the theory expressed above, it is important to link the approach to multi energy systems and demonstrate the automated computer formulation approach considering the electrical components and the mechanical ones as a single system. Nowadays the trend is to prepare mechanical engineers in electronics. The new area of Mechatronics is a perfect place for application of the techniques outlined here. Nise [2] analyzes the process for a d-c motor. A comparison of the approach is useful to illustrate the differences in the conventional approach outlined in Nise [2] and the one proposed here. The figure shown below, is that of a D-C motor.

Physical Model of D-C Motor

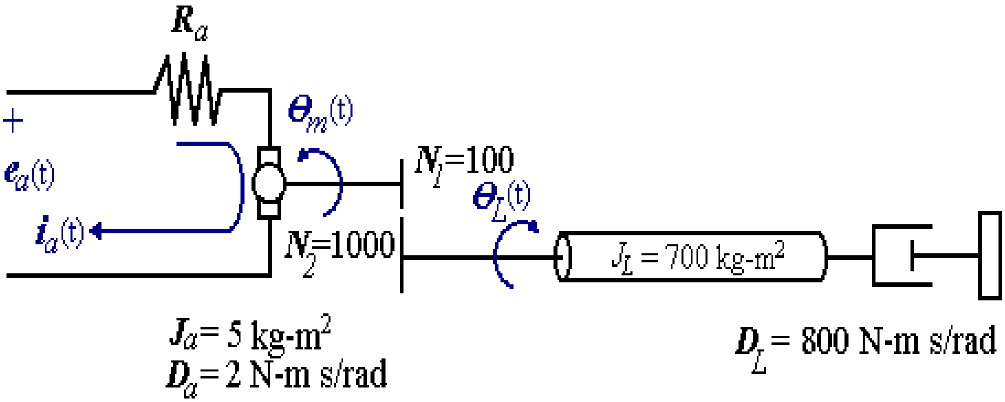


Fig. 3-14 Electromechanical System Model

The process of making the model starts with the identification of the components. The resistors in the circuit, the armature inertia, the gyrator, the gear set, damping components and the load are represented by R,C,GY,I,TF elements. The 1 junction provide the summation points for the voltages in the electrical side and for the torques on the mechanical side.

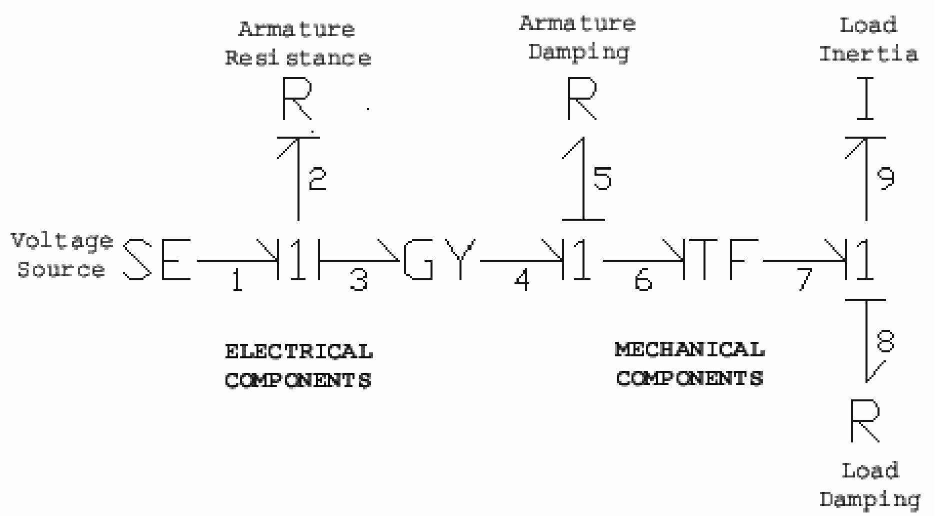
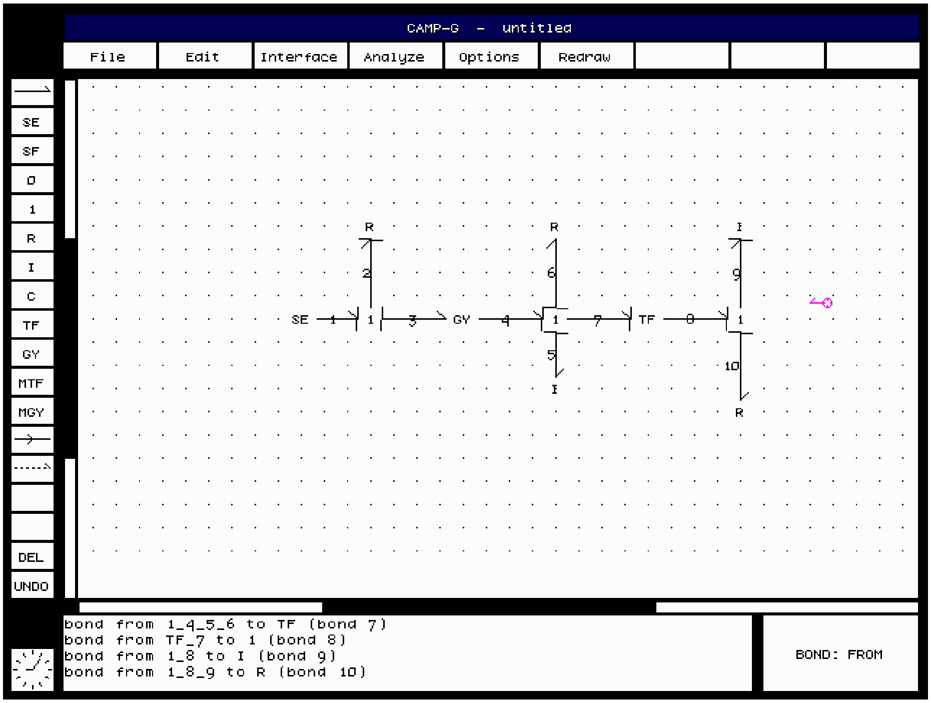


Fig 3-15 Electromechanical System Bond Graph Model

It is obvious in this example that there are two masses involved in the rotational motion, the armature and the load, seen in *Fig. 3-14* (physical model). Since they are coupled together, they are not independent motions. If we disregard this at first and start to model it as two separate inertia elements, the bond graph model will detect derivative causality. This bond graph model is seen in *Fig. 3-15*. In this bond graph model, inertial elements are represented, causing the derivative causality that is depicted by the red "I" element, and the causal mark on that "I" element. *Fig. 3-16*, seen below, shows how the derivative causality is represented in CAMPG.



```
bond from 1_4_5_6 to TF (bond 7)
bond from TF_7 to 1 (bond 8)
bond from 1_8 to I (bond 9)
bond from 1_8_9 to R (bond 10)
```

Fig. 3-16 CAMPG Bond Graph Model

The solution is to join both inertial effects. *Fig. 3-17* shows the bond graph model after the fix has been made. Most of the literature about motors reveals the calculation of the equivalent inertia, but in most cases there is no explanation as to why this is necessary. The bond graph model makes this obvious. What is significant here is that if one translates the schematic directly, a modeling problem is detected. Such detection is a property of bond graph modeling methods which predict this even before any derivation of the equations have been attempted.

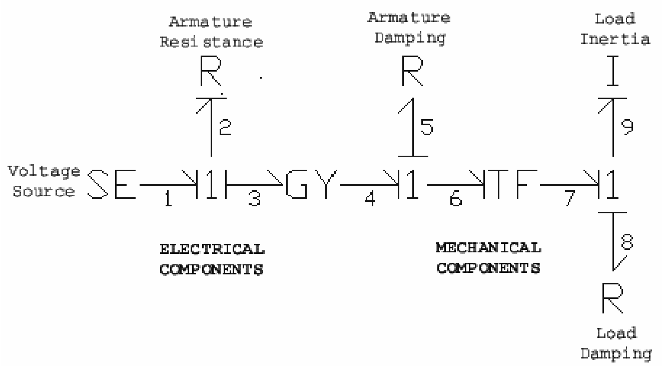
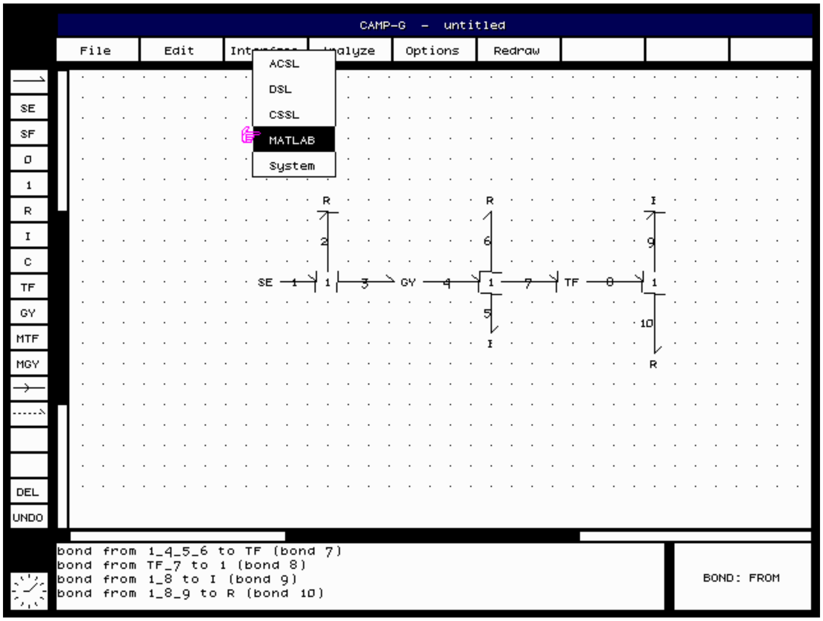


Fig. 3-17 Bond Graph Model

CAMPG is interfaced with Matlab as seen below in *Fig. 3-17*. For detailed step-by-step instructions on creating the bond graph in CAMPG, see the preceding examples.



```
bond from 1_4_5_6 to TF (bond 7)
bond from TF_7 to 1 (bond 8)
bond from 1_8 to I (bond 9)
bond from 1_8_9 to R (bond 10)
```

BOND: FROM

Fig 3-17 CAMPG Display with Bond Graph Model

After interfacing CAMPG with Matlab, CAMPG has generated the .M input files, which describes the equations of motion in first order form with the momentum as the state variable. Speed control can be easily analyzed by tracking the velocity output signal in any of the bonds 8, 9 or 10. The position however needs another integration of the velocity. This can be accomplished in three ways. One way is to create a dummy C element to produce the integration. The second way is to increase the number of states in the MATLAB system equations and include the angular velocity as one of the states so that the position angle is calculated as a result of the integration of all state derivatives. The third way is to wait until the bond graph model is converted to the S domain in MATLAB and be treated as the "plant" and then add a (1/s) term to produce the integration. Incrementing the state space modifies the system matrices and in this case introduces a zero eigenvalue. Here, option two was chosen and the state space was increased to include the angular velocity f9 as one of the derivatives so that integration will produce the angle theta.

What follows, are the listings of the files created by CAMPG after the user has edited them to produce the desired output in graphical form. In this example, there are a few things that are presented in graphical form. They are:

1. Simulation – Position Angle
2. Simulation – Velocity of Armature and Load
3. TF – Step Response – Angular Velocity of Armature and Load
4. TF – Step Response – Position Angle at Load
5. Bode Plot – Load Angular Velocity
6. Bode Plot – Motor Shaft Velocity
7. Bode Plot – Motor Shaft Torque
8. Bode Plot – Position Angle at Load

Much of the files were deleted to save space. The comments that are meant to help the user understand what that particular section of the file are what were deleted to save space.

Campgmod.m

```
%......CAMPGMOD.M - MATLAB MODEL INPUT FILE  ......
   clear
 % ......  Initial conditions  ........
            P9IN= 0 ;
            thetain= 0;
 % Initial conditions vector
   initial = [P9IN, thetain] ;
 % ......System Physical Parameters........
   global R2 G3x4 R6 T7x8 I9 R10
              R2 = 2 ;  G3x4 = 2 ;
              R6 = 2 ;
              T7x8 = 100/1000 ;
              I9 = 700 + 5*((100/1000)^2) ;  R10 = 800 ;
 % ...... External inputs se(t), sf(t) ......
   global SE1
              SE1 = 1 ;
 %..... Simulation Time Control .....
              t0= 0 ;   %  Initial Time
              tf= 3 ;   %  Final Time
              tspan= [t0 tf];
 % ......  Computer Simulation ......
   [t,p_q] = ode23('campgequ',tspan,initial);
 % plots of the velocity and the position of the armature and
the load
   figure(1)
   subplot (212),plot(t,p_q(:,1)/I9,'b'),grid
   title('Simulation - Velocity of armature and load ')
   subplot (211),plot(t,p_q(:,2),'m'),grid
   title('Simulation - Position angle')
 %   end
```

Campgequ.m

```
   function p_qdot = campgequ(t,p_q)
 %  ...........campgequ.m   CAMPG/MATLAB function ...........
 %  System differential equations, state Vectors
 %
```

```
   global R2 G3x4 R6 T7x8 I9 R10
   global SE1
 % System Differential Equations-First Order Form
 %...... Define State Variables ......
         P9= p_q(1) ; theta= p_q(2) ;
 % State variables vector
   % p_q = [P9] ;
 %...... Define derivatives (dp,dq) and output variables (e,f)
......
         e1=SE1 ;                    f9=P9/I9 ;
         f10=f9 ;                    f8=f9 ;
         e10=f10*R10 ;               f7=f8/T7x8 ;
         f6=f7 ;                     f4=f7 ;
         e6=f6*R6 ;                  e3=f4/G3x4 ;
         e2=e1-e3 ;                  f2=e2/R2 ;
         f3=f2 ;                     e4=f3/G3x4 ;
         e7=e4-e6 ;                  e8=e7/T7x8 ;
         e9=e8-e10 ;               dP9=e9 ;
         f1=f2 ;                   dtheta=f9;

 % Derivatives vector
   p_qdot = [dP9; dtheta] ;
```

Campgsym.m

```
         %  CAMPG/MATLAB  - Symbolic State Space Model
   clear
 % Convert system physical parameters to symbols
   syms R2 G3x4 R6 T7x8 I9 R10
 %... Generate A, B matrices corresponding to states p'sand
q's     ...
 % dP9=SE1/R2/G3x4/T7x8-P9/I9/T7x8/G3x4/R2/G3x4/T7x8-
P9/I9/T7x8*R6/T7x8-P9/I9*R10  ...
   A(1,:) = [-1/I9/T7x8/G3x4/R2/G3x4/T7x8-1/I9/T7x8*R6/T7x8-
1/I9*R10, 0];  ...
   B(1,:) = [1/R2/G3x4/T7x8, 0];
   A(2,:) = [1/I9, 0];
   B(2,:) = [0, 0];
 %
   D(3,:) = [1/R2/G3x4, 0];
 % Generate C and D matrices correspoding to outputs e's and
f's
 % f9=P9/I9
```

```
    C(1,:) = [1/I9, 0];
    D(1,:) = [0, 0];
 % f7=P9/I9/T7x8
    C(2,:) = [1/I9/T7x8, 0];
    D(2,:) = [0, 0];
 % e7=SE1/R2/G3x4-P9/I9/T7x8/G3x4/R2/G3x4-P9/I9/T7x8*R6
    C(3,:) = [-1/I9/T7x8/G3x4/R2/G3x4-1/I9/T7x8*R6, 0];
    %D(3,:) = [1/R2/G3x4, 0];
 %theta as an output
   C(4,:) = [0, 1];
   D(4,:) = [0, 0];
 %
   A
   B
   C
   D
 % Define SI matrix
   syms s
 %   Find the size of A and then figure out I
   I=eye(1);
 %  ... Transfer Functions Matrix H ...

    H=C*inv(s*I-A)*B +D
    pretty(collect(H))


    N1=100; N2=1000; R2=2; G3x4=2; R6=2; T7x8=N1/N2;
I9=700+5*((N1/N2)^2); R10=800;

    AA=double(subs(A));
    BB=double(subs(B));
    CC=double(subs(C));
    DD=double(subs(D));


 % Frequency Response
 % Bode Plots
   iu = 1;
   [num,den]=ss2tf(AA,BB,CC,DD,iu)
   printsys(num,den,'s')
 % bode(num,den)


 time = [0:.01:3];
```

```
w = [.1:.1:100];
%
%
figure(2)
subplot(211),step(num(1,:),den,time),grid
title('TF-Step response - Angular velocity of armature and
load')
subplot(212),step(num(4,:),den,time),grid
title('TF-Step Response - Position Angle at load')
xlabel('time(sec)')
%
figure(3)
bode(num(1,:),den,w)
title('Bode Plot - Load Angular Velocity')
%
figure(4)
bode(num(2,:),den,w)
title('Bode Plot - Motor Shaft Velocity')
%
figure(5)
bode(num(3,:),den,w)
title('Bode Plot - Motor Shaft Torque')
%
figure(6)
bode(num(4,:),den,w)
title('Bode Plot - Position angle at load')
%end
```

The transfer functions in the s-domain that were obtained from the CAMPGSYM.M file are as follows…

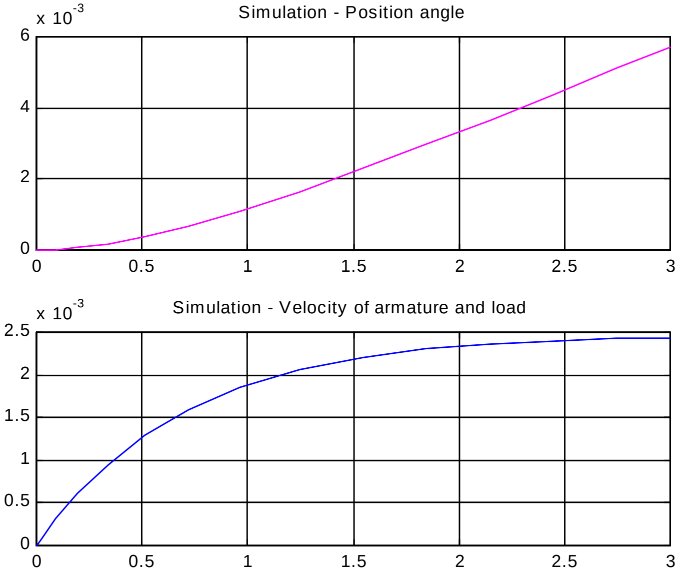
```
num(1)/den =

   0.0035712 s
 --------------
 s^2 + 1.4463 s

num(2)/den =

   0.035712 s
 --------------
 s^2 + 1.4463 s
```

```
num(3)/den =

  0.25 s^2 + 0.28569 s
  --------------------
     s^2 + 1.4463 s

num(4)/den =

     0.0035712
  --------------
  s^2 + 1.4463 s
```

Shown in *Fig. 3-18* and *Fig. 3-19* are two different computations of the system. The top of *Fig. 3-18* is the direct time simulation results obtained by the integration of the differential equations generated in logical sequence and integrated within MATLAB. The bottom of *Fig. 3-19* is generated by the use of the step input on the transfer function generated from the symbolic A,B,C,D matrices generated from the bond graph. The figure on the bottom of *Fig. 3-19* is exactly that of the top of *Fig. 3-18* for the position angle. The other one corresponds to the angular velocity of the armature and load (f9) shown at the bottom of *Fig. 3-183* and corresponding to the top figure of *Fig 3-19.*. This verifies the results not only of the simulation but also of the computer-generated matrices.

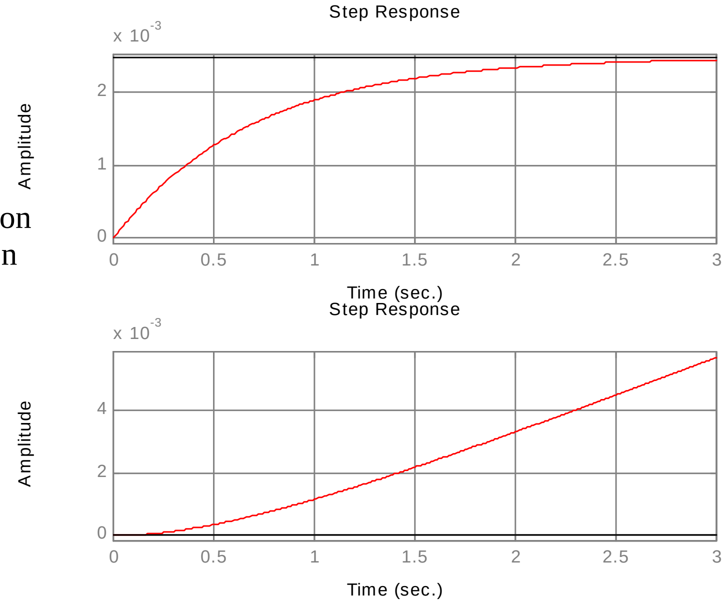
MATLAB Simulation. Solution of differential equations

Fig. 3-18
Time Domain
Simulation



TF – Step Response – Angular Velocity of Armature and Load and Angular Velocity of Armature and Load

Fig 3-19
Using the
Transfer Function
Time Simulation



Once the matrices have been defined, it is easier to get MATLAB to generate frequency response plots. Shown in Figs. 3-20, 3-21, 3-22 and 3-23, seen below, is the Bode Plot of the magnitude and face of the torque output at the shaft (e7) and position angle theta. This variable was chosen to illustrate the fact that this approach will allow the user to obtain transfer functions and simulation results for internal signals of the system since they are calculated during the solution of equations. This is a very useful feature of bond graph models generated in CAMPG because not only the time simulation results can be observed (plotted) for the states but the frequency response and the transfer functions generated for any effort or flow signals internal to the model, not just a single output.

Bode Plot – Load Angular Velocity

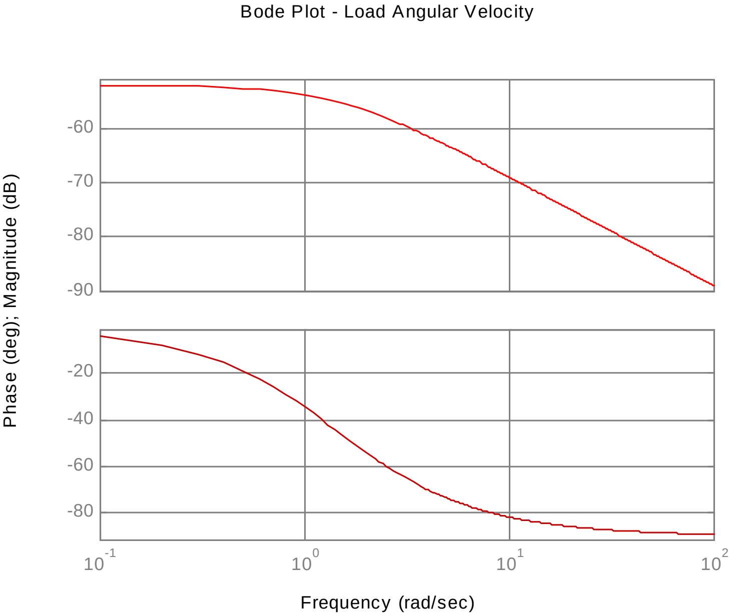
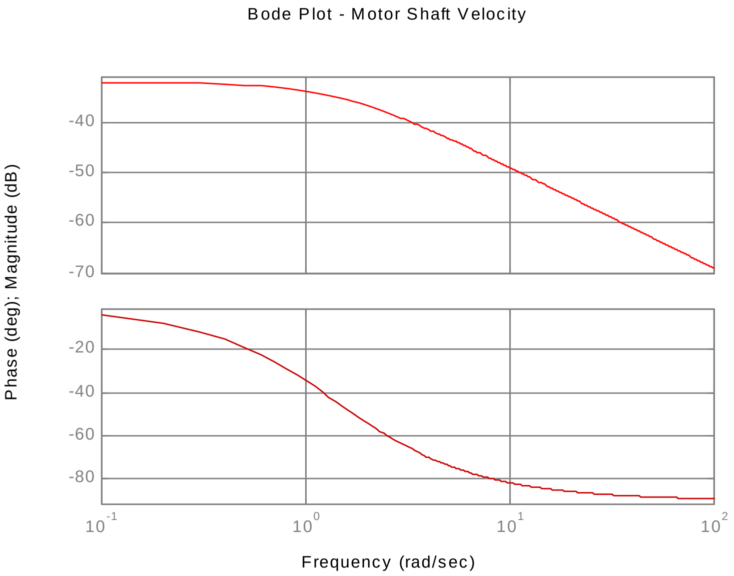


Fig 3-20 Frequency Response Bode Plot

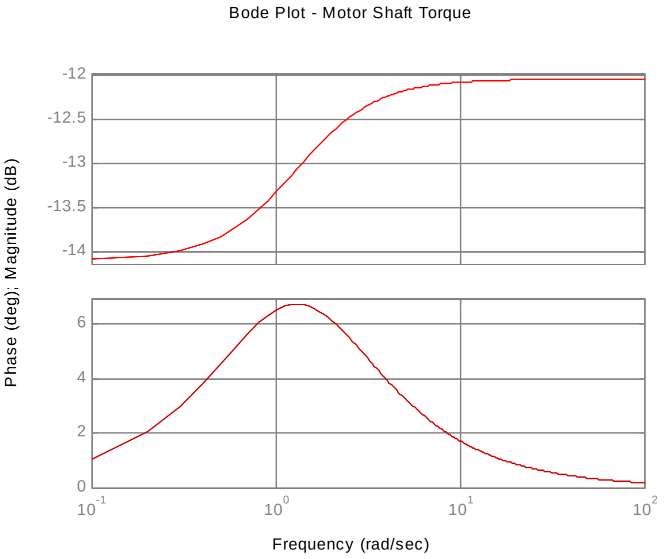
Bode Plot – Motor Shaft Velocity

Fig 3-21
Frequency
Response
Bode Plot
Motor Shaft
Velocity



Bode Plot – Motor Shaft Torque

Fig 3-22
Bode Plot
Motor Shaft
Torque



Bode Plot – Position Angle at Load

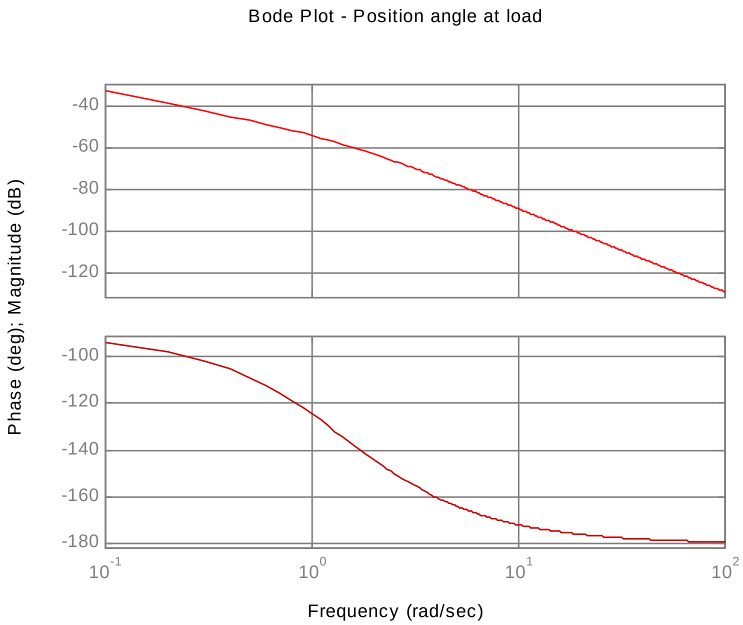


Fig 3-23
Bode Plot
Motor Shaft
Torque

This example illustrates how to obtain transfer functions with the CAMPGSYM.M file. It also is a very good example of how to deal with multienergy systems. The next section will explore other possibilities with nonlinearities and Matlab.

3.9 Nonlinear Example – Gear Train with Backlash

PROBLEM:

Design of precision gear trains requires analysis of forces, velocities, torques and realistic models considering the tolerances and slack between gear teeth. This analysis is important in order to prevent fatigue failure on gear teeth and the transmitting shafts. This will contribute to determine the materials, size of parts and tolerance adjustments that are related to the generation of contact forces. This involves making a dynamic model and performing the analysis of the gear train considering the backlash between the gear teeth.

The system shown in *Fig. 3-24* consists of a gear set and a flywheel. Gear 1 is driven by a cyclic torque described by a harmonic function. The system drives the flywheel through a set of gears having excessive backlash. The shaft connecting gear 2 and the flywheel is not rigid, it has a tensional spring constant of K = 4000 in-lb/radian.

Physical System Model of Drive Train

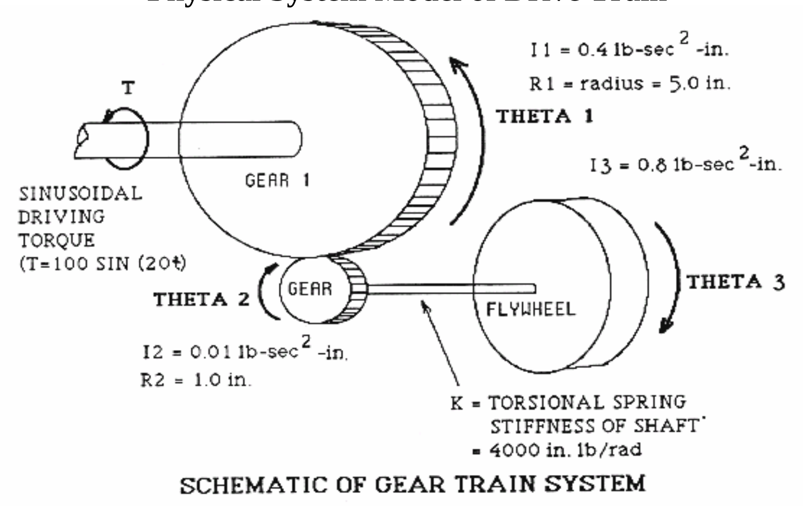


Fig 3-24 Gear Train System

The contact force between the gear teeth is defined by a dead space non-linear function. The force increases linearly when the gears are in contact but is zero when they are not. Since the input torque is a harmonic function, the teeth are not always in contact and therefore a nonlinear model exists. The diagram of this function is shown in *Fig. 3-25*. The position of the gears, forces and velocities are of interest in the design of the gear train.

Nonlinear Dead Space Contact

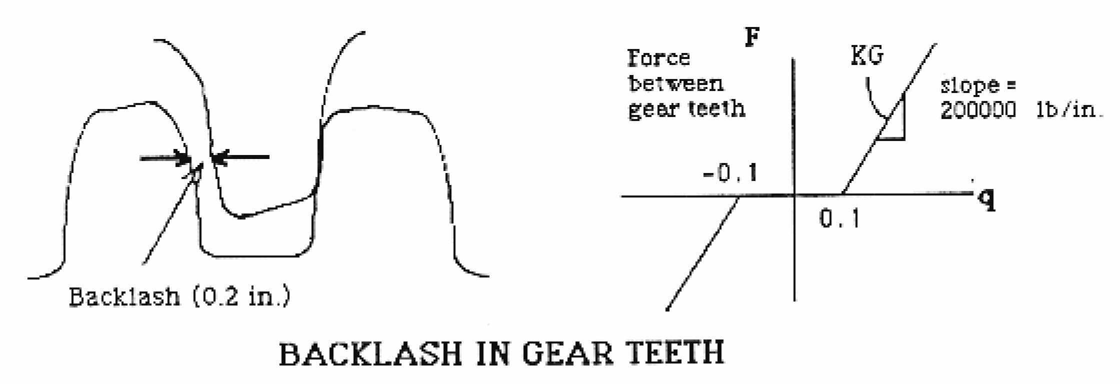


Fig 3-25 Gear Geometry Discontinuity

OBJECTIVES:

1. Generate an engineering model of the gear train shown in *Fig. 3-24.*

2. Transform the engineering model of the real system into a computer model for simulation using the Computer Aided Modeling Program (CAMPG).

2. Using computer simulation in an interactive way generates numerical and graphical output using Matlab.

4. Interpret the results and make design decisions.

PROCEDURE FOR SOLUTION

1. GENERATE AN ENGINEERING MODEL - The system shown in *Fig. 3-24* is the engineering model of the real system. The stiffness elements are the shafts, the inertia element is the flywheel and the gears.

2. GENERATE THE CORRESPONDING BOND GRAPH –

Make a Bond Graph model of the gear train. Consider the inertia of the gears and the flywheel, the compliance effect of the drive shaft and the slack between the gear teeth. *Fig. 3-25* shows this model. The backlash is modeled as a nonlinear compliant element (C) because the constitutive relation between contact force and the relative displacement is defined in *Fig. 3-25*. The force function is directly related to the relative displacement between the teeth. This relative displacement at the gear teeth point of contact is calculated by the integration of the relative velocity between the two gears. The relative tangential velocity is obtained by multiplying the angular velocity of the gear by their respective radius and finding the difference in tangential velocities a the point where the gears are in contact. This is accomplished by the TF elements that make this transformation between the angular velocity and the tangential velocity. The C element performs the integration and controls also the force using the defined DEAD SPACE function that represents the time the gears are in contact as well as when they are not.

Bond Graph Model

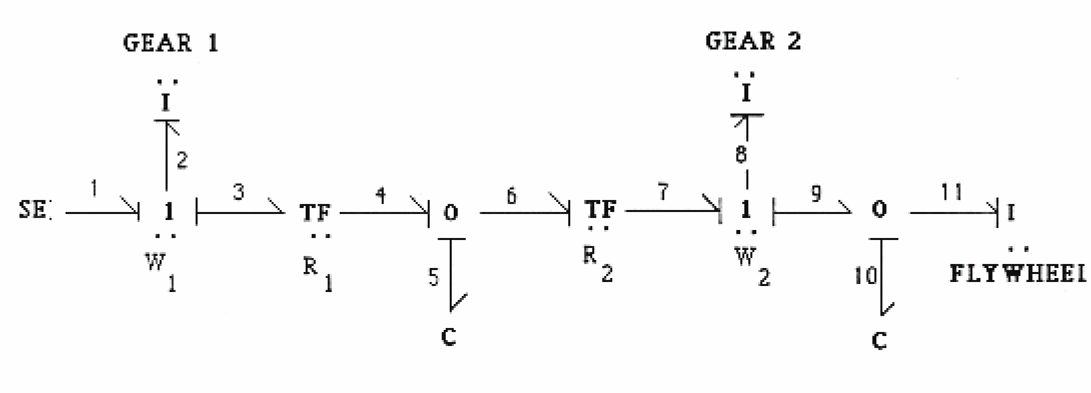
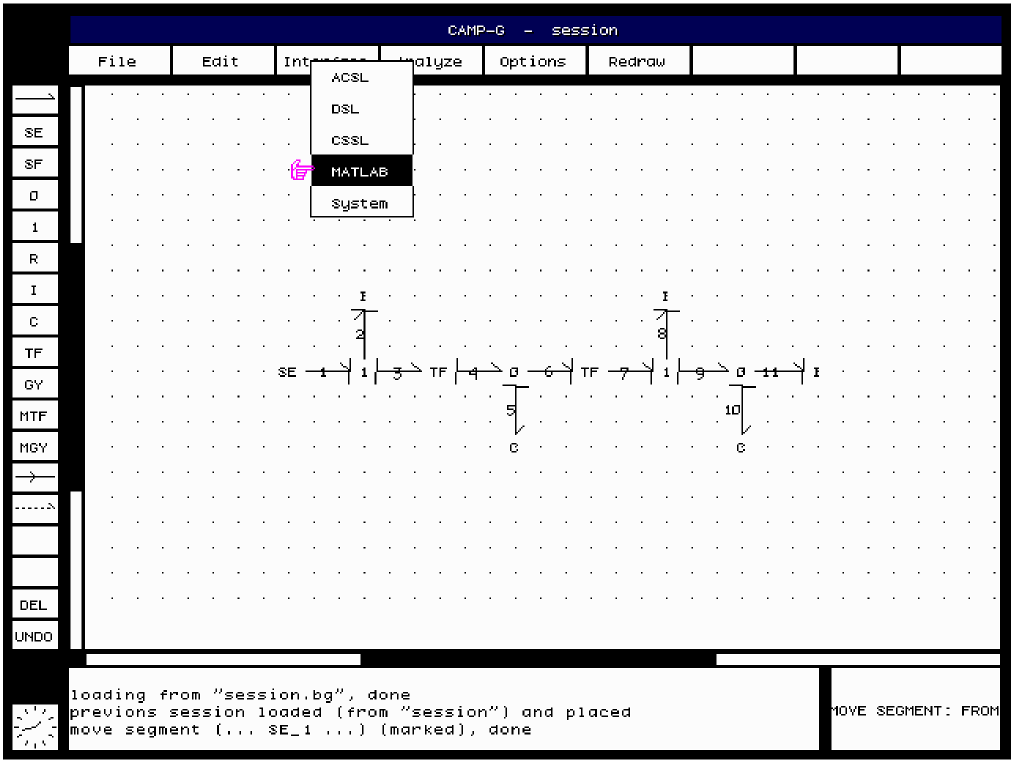


Fig 3-26 Gear Train Bond Graph Model

Bond Graph Model in CAMPG



```
loading from "session.bg", done
previons session loaded (from "session") and placed
move segment (... SE_1 ...) (marked), done
```

Fig 3-27 CAMPG Interface Menu

3. CAMPG - Generate a description of the graph using the graphics capabilities of the Computer Aided Modeling Program with Graphical input (CAMPG). This model is shown in *Fig. 3-27*.

   In sections 3.7 and 3.8 the linear model was constructed using the SYSTEMATIC method. In the case of the gear teeth, the SEQUENTIAL method is used to generate the bond graph and demonstrate how to construct bond graph models using this method and CAMPG. Just as a brief reminder, the SEQUENTIAL method consists of assembling of all bonds immediately following the placement of the elements and 0 or 1 junctions. This method helps to illustrate other editing features of CAMPG such as the moving of whole bond graphs or parts of them to other parts of the screen.

The bond graph of *Fig. 3-27* was constructed using the following steps:

CAMPG	<CR>	Start CAMPG and brings up the logo containing the user name and the license number. Please refer to this number for maintenance and updates.
(space bar)	<CR>	This clears the screen preparing it for a drawing. Any other character or movement of the mouse will do the same.
EDIT	(CUR)	The next three steps clear the session file. If you have no previous SESSION.BG file. These steps are not necessary.
DELETE	(CUR)	
ALL	(CUR)	
YES	(CUR)	
SE	(CUR)	There is a box on the left icon menu which has the SE symbol in it. This is the SOURCE EFFORT element in the bond graph. Pick the SE with the mouse.
(Left of screen)	(CUR)	Place the (SE) on the screen by moving the cursor to the middle of the vertical left edge of the drawing screen and a couple of grids to the right and clicking the left button of the mouse. The model can start in any location of the screen.

1 (CUR) Pick the 1 junction from the menu on the left and place it two grids to the right of the SE element. Both elements are red now.

(CUR) You will see on the Status Box the message "Bond: from" and the cursor turned to a small circle and an arrow pointing left. Click on the SE element. The cursor will change direction as a circle and an arrow pointing right. The Status Box reads "Bond: to". Click the cursor on the 1 junction or as close to it as you can. The bond that joins the SE element and the 1 junction will be displayed along with a bond number and the causality assignment.

Note that the 1 is red, this indicates the bond graph is not complete. Any bond or element in red indicates some difficulty with the graph. The user can get an explanation in any case. To do this click the mouse on the ANALYZE button, choose explain (the cursor will change) and then click on 1 element. The message displayed on the dialogue box is "explain 1_1: too few bonds".

I (CUR) Now select an (I) element by clicking the mouse while the cursor is on the I button on the elements menu. Place these two grids above the 1 junction by moving the cursor and clicking the mouse. The distance is arbitrary.

(CUR) Draw the bond between the 1 and the I element; click the mouse on the 1 and then on the I. The cursor will change direction on each click and the bond 2 will appear on the screen.

TF (CUR) Select the TF element from the menu and place it to the right of the 1 junction.

(CUR) Status Box reads "Bond: from" and the cursor turned to a small circle and an arrow pointing left. Click on the 1 junction. The cursor again changes direction as a circle and an arrow pointing right. The Status Box reads "Bond: to". Click the cursor on the 1 junction or as close to it. The bond that joins the junction and the element will be displayed with its corresponding bond number one higher than the previous one and causality assignment.

0 (CUR) Pick a 0 junction, place it to the right of the TF.

TF(screen) (CUR)

0 (screen) (CUR) This should create a bond from the (TF) element to the (0) junction.

C (CUR) Select an (C) and place it below the (0).

0 (screen) (CUR) Click on the (0) element on the screen.

C (screen) (CUR) Click on the (C) element on the screen. A bond should appear between these two elements.

TF (CUR) Select (TF) and place it to the right of the 0 junction.

0 (screen) (CUR)

TF(screen) (CUR) This should create a bond from the (0) junction and the (TF) element. The number of the bond will appear in the middle of the bond as it has for all the other bonds.

1 (CUR) Pick a 1 junction from the menu and place it to the right of the TF6x7.

TF(screen) (CUR) Click the mouse on the TF for FROM status.

1 (screen) (CUR) Click on the 1 junction. Note again that the numbers of the bonds appear automatically in the middle of the bonds. In this case (7).

I (CUR) Click on the I icon in the menu. Place the I above the last 1 junction.

1 (screen) (CUR)

I (screen) (CUR) Generates a bond between the (1) and the (I) element.

0 (CUR) Pick the (0) from the menu, place it the right of the last (1) junction.

1 (screen) (CUR)

0 (screen) (CUR) Draws a bond between 1 and the 0 junction.

C (CUR) Pick (C) from the menu and place it below the last (0) junction.

0 (screen) (CUR)

C (screen) (CUR) Generates bond between (0) and (C).

I (CUR) Pick (I) and place it to the right of the (0) junction.

0 (screen) (CUR)

I (screen) (CUR) This step completes the bond graph by drawing a bond from the last (0) junction to the (I) element. Now the whole bond graph can be moved to the right to have it on the center of the screen. This is done with the following steps.

EDIT (CUR) Pick the EDIT button and select the MOVE button. There will be two choices. SINGLE and SEGMENT. Pick SEGMENT .

SEGMENT(CUR) The cursor will change shape to a cross. Click the mouse on the SE element (it can be any other element or junction). The bond graph segment will turn blue.

(CUR) Move the cursor to the desired new location for the element picked. The bond graph will be redrawn in the new location.

All junction and elements have their corresponding bonds, numbers, and causality marks. If there is any one bond or element on the screen that it is red, use the ANALYZE button and pick EXPLAIN, then click on the red bond or element. A message on the dialogue box will indicate the status or error message.

4. GENERATE THE MATLAB FILES - Continuing from the previous step, once the bond graph has been completed pick the INTERFACE button and within it the MATLAB option, seen *Fig. 3-27.* CAMPG will generate the CAMPGMOD.M, CAMPGEQU.M and CAMPGSYM.M files used to perform system simulation. In this example the CAMPGMOD.M and CAMPGEQU.M files are going to be used.

5. ENTER PARAMETER VALUES - Edit the CAMPG model to enter the linear and non-linear constitutive relations of physical elements into the CAMPGEQU.M file. This file completed was shown in the previous section. Note the non-linear constitutive relation of the C5 element is entered as a modification of the linear version of E5 = Q5/C5. One method that will represent this nonlinearity is shown here:

   ```
   if Q5 < -.1
   e5=KG*Q5;
   elseif Q5 > .1
   e5=KG*Q5;
   else
   e5=0;
   end
   ```

   This is input into the CAMPGEQU.M file in place of the line that originally defined e5. Below is a listing of the CAMPGMOD.M and CAMPGEQU.M files.

   The model causality and power flow tables are generated in the CAMPGMOD.M file in order to assist the user to verify the input model structure and power flow.

   The instructions at the beginning as well as the explanation of the variables in different energy domains or the verification of causality and power flow can be included in the CAMPGMOD.M file as CAMPG generates this in the form so that Matlab considers that as no executable statements. The user can erase one or both of these information sections.

CAMOGMOD.M Listing.

```
 %    CAMPG/MATLAB - GENERATED MODEL DESCRIPTION:
 %      The following files have been generated
 %      campgmod.m  => m file containing model parameters
 %                    initial conditions, sources and
simulation controls
 %      campgequ.m  => m function containing the system
 %                    first order differential equations
```

```
 %      campgsym.m  => m file containing system matrices in
symbolic form
 %
 %    For simulation and control, edit these files
 %     Enter values for physical parameters, initial
 %     conditions,inputs and time controls
 %     in places where the ?? marks appear
 %     Standard generalized variables in Bond Graph notation
used.
 %
 %......CAMPGMOD.M - MATLAB MODEL INPUT FILE  ......
   clear all
 % ......  Initial conditions  ........
              P11IN= 0 ; P8IN= 0 ;
              P2IN= 0 ; Q5IN= 0 ;
              Q10IN= 0 ;
 % Initial conditions vector
   initial = [P11IN; Q10IN; P8IN; P2IN; Q5IN; 0; 0; 0] ;
 % ......System Physical Parameters........
   global I2 T3x4 C5 T6x7 I8 C10 I11 counter Efforts
              I2 = .4 ;
              T3x4 = 5 ;
              %C5 = ?? ;  Using non-linear relationship
instead.
              T6x7 = 1 ;
              I8 = .01 ;
              C10 = 1/4000 ;  I11 = .8 ;
              counter = 1;
 % ...... External inputs se(t), sf(t) ......
 %  global SE1
 %             SE1 = 100*sin(20*t) ;
 %..... Simulation Time Control .....
              t0= 0 ;   %  Initial Time
              tf= 1 ;   %  Final Time
              tspan= [t0 tf];
 % ......  Computer Simulation ......
 %  Solution of system equations using Matlab "ode23" function
 %  The campgequ.m function contains the system differential
 %  equations in state variable form.
 %
 %  It returns the vector [t,p-q] where:
 %  t = time and p-q = vector of state variables
 %  For matlab version 4.2 use:
 %  [t,p_q] = ode23('campgequ',t0,tf,initial);
```

```
  status = odeset('outputfcn','esandfs');
  [t,p_q] = ode23('campgequ',tspan,initial,status);
%          P11= p_q(1) ; %          Q10= p_q(2) ;
%          P8= p_q(3) ; %          P2= p_q(4) ;
%          Q5= p_q(5) ;
% State variables vector
  % p_q = [P11; Q10; P8; P2; Q5] ;
%
radeg=360/(2*pi);

% Sample Matlab structure for plotting simulation results
%Figure with the Theta's
  figure(1)
  subplot (311),plot(t,p_q(:,6)*radeg,'r'),grid
  title('Theta 1')
  subplot (312),plot(t,p_q(:,7)*radeg,'b'),grid
  title('Theta 2')
  subplot (313),plot(t,p_q(:,8)*radeg,'r'),grid
  title('Theta 3')
  %New figure with W's
  figure(2)
  subplot (311),plot(t,Efforts(:,2),'r'),grid
  title('W 1')
  subplot (312),plot(t,Efforts(:,3),'b'),grid
  title('W 2')
  subplot (313),plot(t,Efforts(:,4),'r'),grid
  title('W 3')
  %New figure with accellerations...
  figure(3)
  subplot (311),plot(t,Efforts(:,5)*radeg/I2,'r'),grid
  title('WD1')
  subplot (312),plot(t,Efforts(:,5)*radeg/I8,'b'),grid
  title('WD2')
  subplot (313),plot(t,Efforts(:,7)*radeg/I11,'r'),grid
  title('WD3')
  %New figure with Twist, Force and Input torque...
  figure(4)
  subplot(311),plot(t,p_q(:,2)*radeg,'r'),grid
  title('Twist')
  subplot(312),plot(t,Efforts(:,1),'b'),grid
  title('Force')
  subplot(313),plot(t,100*sin(20*t),'r'),grid
  title('Input Torque')
  %New figure with E10, E2 and F vs. Q5...
```

```
   figure(5)
   subplot(311),plot(t,Efforts(:,8),'r'),grid
   title('E10')
   subplot(312),plot(t,Efforts(:,5),'b'),grid
   title('E2')
   subplot(313),plot(Efforts(:,9),Efforts(:,1),'r'),grid
   ylabel('Force'),xlabel('Q5')
   %New figure with Q5...
   figure(6)
   plot(t,Efforts(:,9),'r'),grid
   title('Q5')
 %   end
 %

            %..........BOND GRAPH NOTATION.............
          %  GENERALIZED VARIABLES BOND GRAPH NOTATION :
%----------------------------------------------------------------------
%                       MECHANICAL         ELECTRICAL    HYDRAULIC
%              | TRANSLATION| ROTATION  |            |
%--------------|------------|-----------|------------|----------------
%E (Effort)    |Force       |Torque     |Voltage     |Pressure
%F (Flow)      |Velocity    |Ang Vel.   |Current     |Volume Flow Rate
%Q (Gen Disp)  |Displacement|Angle      |Charge      |Volume
%P (Gen Momentum)|Momentum  |Ang.Moment.|Flux Linkage|Pressure Moment.
%----------------------------------------------------------------------
% TF (M) (Transformer Modulus)      SE Source Effort
% GY (R) (Gyrator Modulus)          SF Source Flow
%----------------------------------------------------------------------

       %*********************    ********************
            %....... BOND GRAPH ANALYSIS .......

 %SYSTEM  DESCRIPTION:


% POWER FLOW:
% BOND    FROM                                  TO
% ----    ----                                  --
%   1   SE_1                                  1_1_2_3
%   2   1_1_2_3                               I_2
%   3   1_1_2_3                               TF_3_4
%   4   TF_3_4                                0_4_5_6
%   5   0_4_5_6                               C_5
%   6   0_4_5_6                               TF_6_7
%   7   TF_6_7                                1_7_8_9
%   8   1_7_8_9                               I_8
%   9   1_7_8_9                               0_9_10_11
%  10   0_9_10_11                             C_10
%  11   0_9_10_11                             I_11

% CAUSALITY FLOW:
```

```
% NOTE:  FROM -----| TO

% BOND    FROM                                TO
% ----    ----                                --
%   1   SE_1                                1_1_2_3
%   2   1_1_2_3                             I_2
%   3   TF_3_4                              1_1_2_3
%   4   0_4_5_6                             TF_3_4
%   5   C_5                                 0_4_5_6
%   6   0_4_5_6                             TF_6_7
%   7   TF_6_7                              1_7_8_9
%   8   1_7_8_9                             I_8
%   9   0_9_10_11                           1_7_8_9
%  10   C_10                                0_9_10_11
%  11   0_9_10_11                           I_11

% End of model
```

CAMPGEQU.M Listing

```
   function p_qdot = campgequ(t,p_q)
 %  ...........campgequ.m   CAMPG/MATLAB function ...........
 %  System differential equations, state Vectors
 %
   global I2 T3x4 C5 T6x7 I8 C10 I11 vect_out
 %  global SE1
 % System Differential Equations-First Order Form
 %...... Define State Variables ......
         P11= p_q(1) ;         Q10= p_q(2) ;
         P8= p_q(3) ;         P2= p_q(4) ;
         Q5= p_q(5) ;


         Q2= p_q(6);  Q8= p_q(7);  Q11= p_q(8);
         SE1 = 100*sin(20*t);
         KG = 200000;
 % State variables vector
   % p_q = [P11; Q10; P8; P2; Q5] ;
 %...... Define derivatives (dp,dq) and output variables (e,f)
......
         e1=SE1 ;                    f2=P2/I2 ;
         f3=f2 ;
         %
         %e5 is non-linear and it is a function of Q5
         %Making e5 a function of Q5 and accounting for the
.2in backlash spacing..
         if Q5 < -.1
```

```
            e5=KG*Q5;
         elseif Q5 > .1
            e5=KG*Q5;
         else
            e5=0;
         end
         %
         %continuing with linear constitutive relations...
         f4=f3*T3x4 ;                e6=e5 ;
         e7=e6/T6x7 ;                f8=P8/I8 ;
         e10=Q10/C10 ;               f9=f8 ;
         f11=P11/I11 ;               e11=e10 ;
       dP11=e11 ;                    f1=f2 ;
         e4=e5 ;                     f7=f8 ;
         e9=e10 ;                    f10=f9-f11 ;
       dQ10=f10 ;                    e3=e4*T3x4 ;
         f6=f7/T6x7 ;                e8=e7-e9 ;
       dP8=e8 ;                      e2=e1-e3 ;
         f5=f4-f6 ;                dP2=e2 ;
         dQ5=f5 ;
         %
         %additional state variables
         dQ2=f2;  dQ8=f8;  dQ11=f11;

% ... Build vector of derivatives p_qdot(n)...
 %        p_qdot1) = dP11 ; %        p_qdot2) = dQ10 ;
 %        p_qdot3) = dP8 ; %        p_qdot4) = dP2 ;
 %        p_qdot5) = dQ5 ;
 % Derivatives vector
   p_qdot = [dP11; dQ10; dP8; dP2; dQ5; dQ2; dQ8; dQ11] ;

 % ...  Define output vectors (efforts,flows)...

 %this is to make plotting easy...
 vect_out = [e5 f2 f8 f11 e2 e8 e11 e10 Q5];
```

6. RUN MATLAB - Using the CAMPG/MATLAB model, perform a computer simulation to obtain the values of variables that will help make design decisions. These include the torques, forces and displacements of the gears, the flywheel and the shaft. These variables are:

F	Force between teeth
Q5	Relative displacement between teeth
W1	Angular velocity of gear 1
W2	Angular velocity of gear 2
W3	Angular velocity of flywheel
Theta1	Angle of rotation of gear 1
Theta2	Angle of rotation of gear 2
Theta3	Angle of rotation of flywheel
Twist	Shaft angle of twist
Wd1	Angular acceleration of gear 1
Wd2	Angular acceleration of gear 2
Wd3	Angular acceleration of flywheel
SE1	Input torque
E2	Torque on gear 1
E10	Torque on shaft

The commands that create these new outputs are in the CAMPGEQU.M file shown above, and they are shown by them selves below.

F	Obtained by plotting the Force on the teeth vs. the distance between the teeth, Q5.
Q5	Obtained by plotting Q5 vs. Time.
W1	Obtained by plotting F2 vs. Time.
W2	Obtained by plotting F8 vs. Time.
W3	Obtained by plotting F11 vs. Time.
Theta1	Obtained by plotting Q2*360/(2*pi) vs. Time.
Theta2	Obtained by plotting Q8*360/(2*pi) vs. Time.
Theta3	Obtained by plotting Q11*360/(2*pi) vs. Time.
Twist	Obtained by plotting Q10*360/(2*pi) vs. Time.
Wd1	Obtained by plotting (E2*360)/(2*pi*I2) vs. Time.
Wd2	Obtained by plotting (E8*360)/(2*pi*I8) vs. Time.
Wd3	Obtained by plotting (E11*360)/(2*pi*I11) vs. Time.

SE1	Obtained by plotting 100*sin(20*Time) vs. Time
E2	Obtained by plotting E2 vs. Time.
E10	Obtained by plotting E10 vs. Time.

7. MODIFICATION OF CAMPGMOD.M IN SIMULATUON - Using Matlab interactively, is very useful and the designer gains an insight of the system and its performance as well as modeling errors. The numerical and graphical results can be obtained very quickly and without much typing of commands and specification for plots if these specification are typed into the CAMPGMOD.M file. The commands added to the CAMPGMOD.M file shown below were used to study the dynamic performance of the gear train. Once these commands are added to the file, plots are automatically generated each time the user runs the simulation. The plotting output commands are shown below.

```
%Figure with the Theta's
figure(3)
subplot (313),plot(t,p_q(:,6)*radeg,'r'),grid
title('Theta 1')
subplot (312),plot(t,p_q(:,7)*radeg,'b'),grid
title('Theta 2')
subplot (311),plot(t,p_q(:,8)*radeg,'r'),grid
title('Theta 3')
%New figure with W's
figure(2)
subplot (313),plot(t,Efforts(:,2),'r'),grid
title('W 1')
subplot (312),plot(t,Efforts(:,3),'b'),grid
title('W 2')
subplot (311),plot(t,Efforts(:,4),'r'),grid
title('W 3')
%New figure with accellerations...
figure(1)
subplot (313),plot(t,Efforts(:,5)*radeg/I2,'r'),grid
title('WD1')
subplot (312),plot(t,Efforts(:,6)*radeg/I8,'b'),grid
title('WD2')
subplot (311),plot(t,Efforts(:,7)*radeg/I11,'r'),grid
title('WD3')
%New figure with Twist, Force and Input torque...
```

```
figure(4)
subplot(312),plot(t,p_q(:,2)*radeg,'r'),grid
title('Twist')
subplot(313),plot(t,Efforts(:,1),'b'),grid
title('Force')
subplot(311),plot(t,100*sin(20*t),'r'),grid
title('Input Torque')
%New figure with E10, E2 and F vs. Q5...
figure(5)
subplot(312),plot(t,Efforts(:,8),'r'),grid
title('E10')
subplot(311),plot(t,Efforts(:,5),'b'),grid
title('E2')
subplot(313),plot(Efforts(:,9),Efforts(:,1),'r'),grid
ylabel('Force'),xlabel('Q5')
%New figure with Q5...
figure(6)
plot(t,Efforts(:,9),'r'),grid
title('Q5')
```

DESIGN CRITERIA

The contact force between teeth depends upon the relative position of the gears due to the slack between them. The contact force is zero in position where the teeth are not in contact but increases proportionally to the displacement after contact has been made. Using this nonlinear relation and a cyclic input torque, it is important to find the torques generated internally on the gears and the shaft due to the dynamics of the system.

It is necessary to find values and graphical plots for the design variables such as angles, angular velocities, accelerations and the dynamic forces acting on the different components. These will assist the designer to prevent fatigue failure because now the stress levels can be calculated. The position of the gears is important to calculate as knowledge of the angular displacements can assist in satisfying geometric constraints and determining the acceptable backlash.

RESULTS

The results of the calculations are shown in the following figures. They show plots of the angular velocities, angular accelerations and torques and all other design variables of interest established in the design criteria.

Other variables can be calculated or plotted besides the ones explained in the design criteria and plotted below because CAMPG has generated all internal variables and all were calculated as a result.

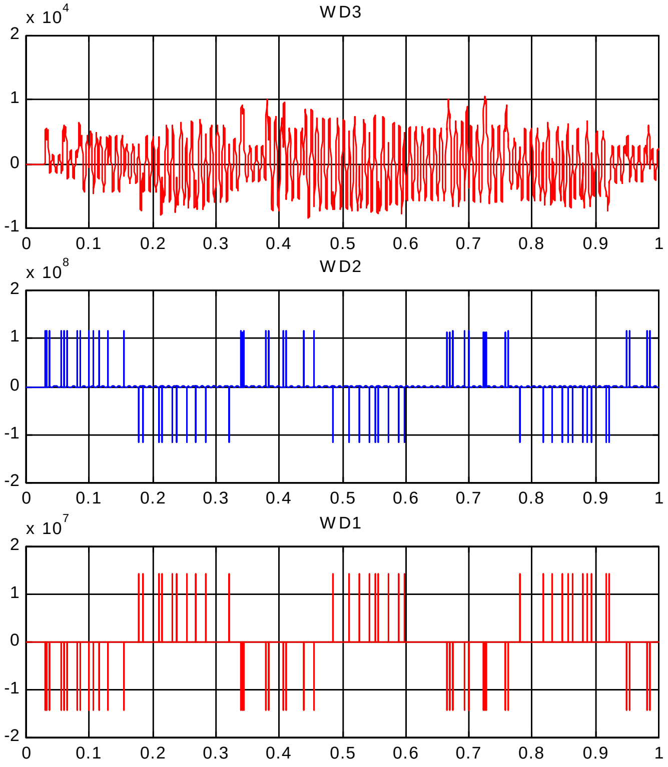


Fig. 3-28 Angular Acceleration

Figure 3-28 - Since the input is a torque; a causal effect is the acceleration and velocity of the gears. These variables are affected by the discontinuity of the contact made among the gear teeth. The plot at the bottom is the plot shows that gear 1 is accelerating under a basic harmonic function but the positive and negative peaks are accelerations and decelerations due to the dynamics of the gear train. The figure in the middle is the plot of the acceleration of Gear 2. It is an order of magnitude bigger and contains higher peeks of acceleration and deceleration. This can be explained due to several factors. The most influential ones are the gear ratio and the separations and sudden contact that the gears experience at a high frequency. The acceleration at the flywheel is affected by the stiffness of the shaft; it is lower in this case because the shaft is flexible.

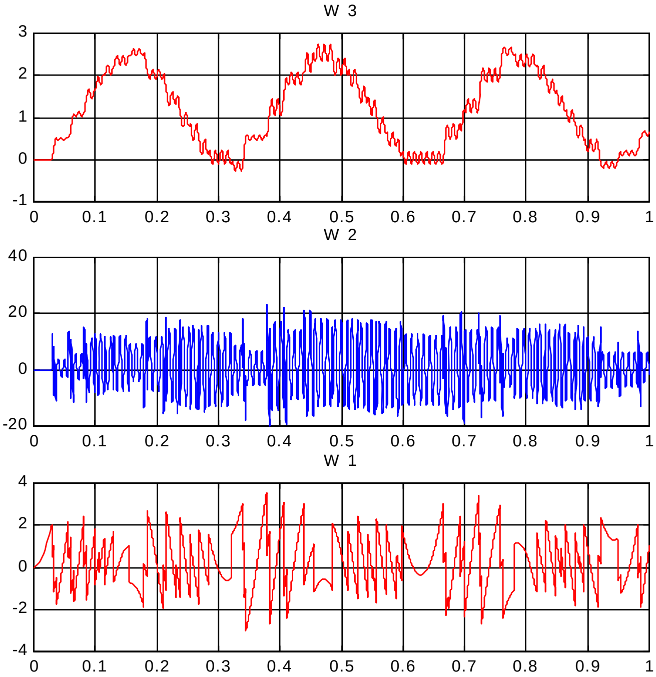


Fig 3-29. Angular Velocities

Figure 3-29 - This figure shows the angular velocity of the gears and also of the flywheel. The bottom figure shows a nonlinear function while the

flywheel velocity appears as a periodic function. The changes in velocity of gear 2 occur at a high frequency. This is due to the vibration of the gear train on both sides of gear 2 and rapid changes in the motion of gear 1 and the backlash between gear teeth. The influence of the compliant shaft is seen in the plot of the angular velocity of the flywheel (top plot). Changes are smoother in the shaft velocity since this is a capacitive element and therefore stores energy. Mathematically this element performs integration of W3 and therefore eliminates the noise seen in that function. This change is obvious between WD3 in *Fig. 3-28* and W3 in *Fig. 3-29*.

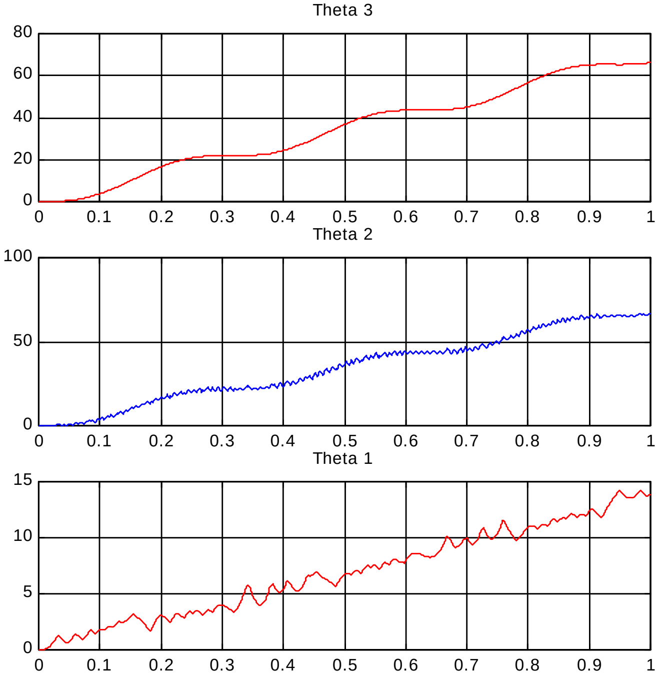


Fig 3-30 Position Angles

Figure 3-30 - This figure compares the position angle of rotation of the gears and the angle of twist of the shaft. It shows the geometrical configuration of the gear train. It can be seen from this figure how the gear

train starts to move in one direction while the angle of twist in the shaft changes to +2 to -2 degrees.

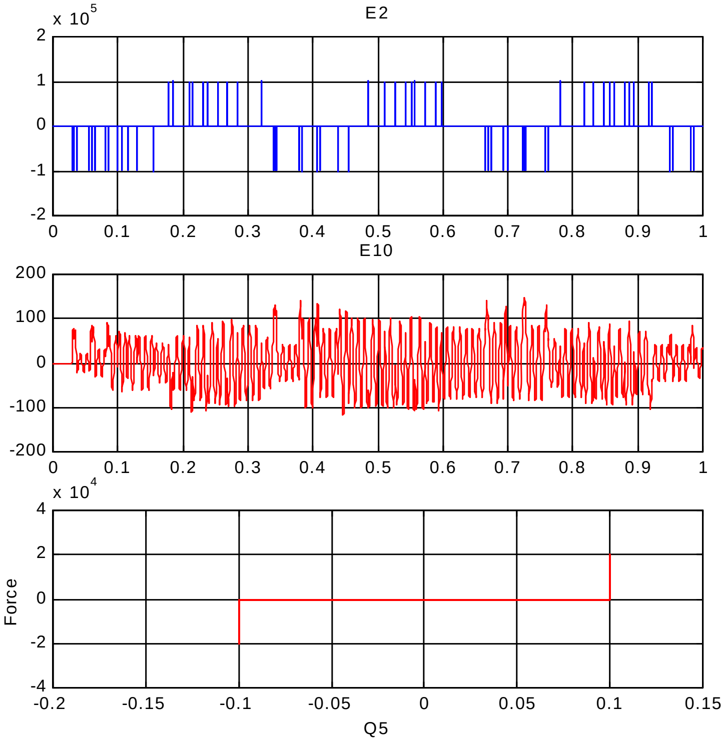


Figure 3-31 Torque Display

Figure 3-31 - Shows the torque at the input gear. This plot is similar to the one of the acceleration. The relationship can be explained by Newton's Law in rotation since the rotational moment of inertia is the relational constant. Therefore the torque is proportional to the angular acceleration of gear 1. *Fig. 3-31* gives a good understanding of the stress level changes within the shaft and therefore can be used to design the shaft.

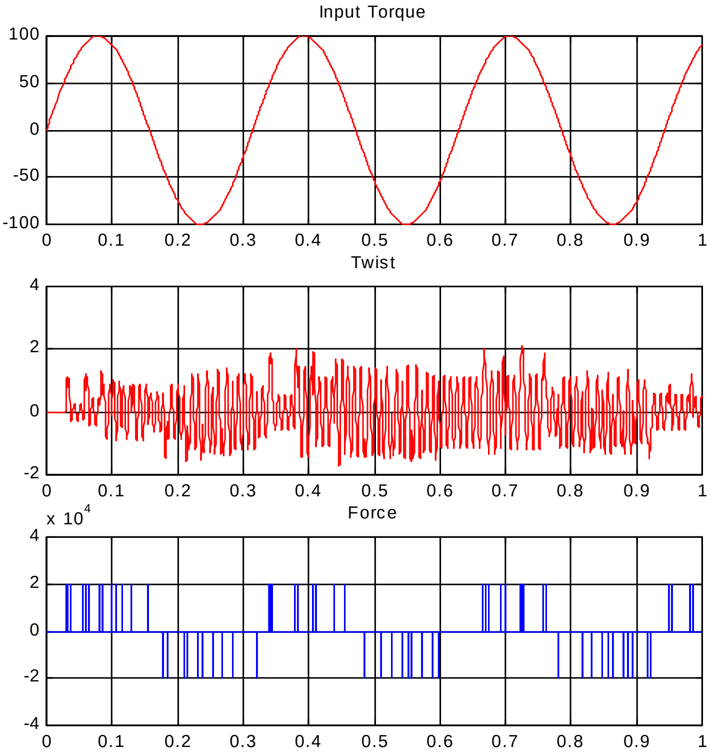


Fig. 3-32   Forces

Figure 3-32 - This figure shows in detail the torque input function, position and relation between contact forces and displacements.

The top figure represents the input torque of gear 1. The bottom figure shows the relation between force and displacement. This is the fundamental nonlinear constitutive relation that allows the representation of the backlash as a (C) element in the bond graph model.

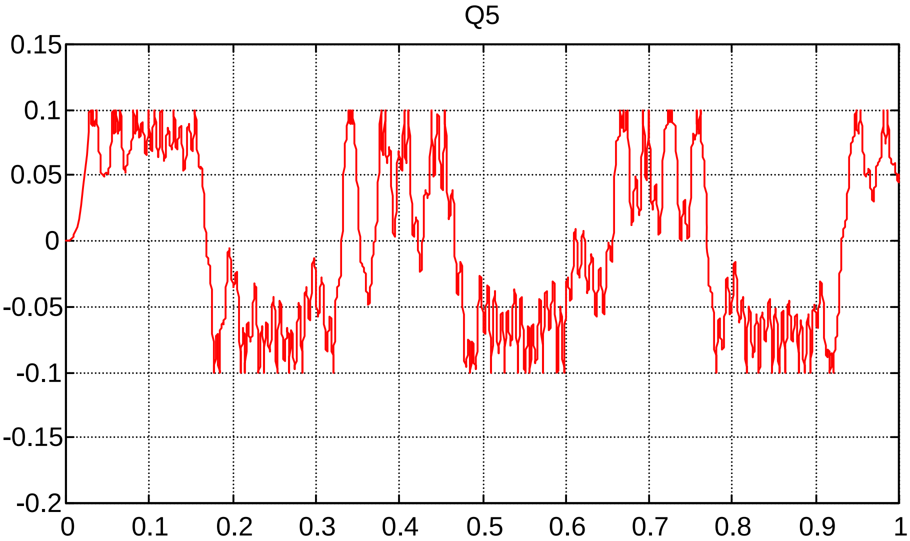


Fig 3-33 Teeth Gear Position

Figure 3-33 - This is a plot of the teeth gears position; it clearly shows how the gears separate as Q5 changes sign. It shows also that the contact is not completely uniform but it is influenced by some jitter motion due to the dynamics of the other components of the gear train.

3.10 CAMPG/MATLAB – Hydroelectric Power Plant with Surge Tanks

This section will show the user another type of nonlinearity and how to deal with it. This will show the user how to deal with a source of flow that is nonlinear.

POWER PLANT

A hydroelectric power plant has a turbine that delivers power when the flow, Qo, is 1 cubic meter per second. When the generator trips off the line, Qo is reduced to zero in 0.1 seconds, to prevent over speeding. There are two surge tanks to prevent excessive pressures in the standpipe.

OBJECTIVES:

1. Design the tanks so that the areas will be such that no overflowing will occur when Qo is shut down.

2. If the slope of the standpipe changes how does the surge levels in the tanks change if everything else is held constant. (To change the slope, keep the lengths of the of the standpipe segments the same. That means that the change in heights of the standpipe segments will have to change to change the slope of them.)

3. Generate graphical displays using the computer and show the levels of water in the tanks and the corresponding pressures in the standpipe segments.

4. Also use tabular displays to show the peak pressure in the standpipes and the peak height is the tanks.

Model of Physical System

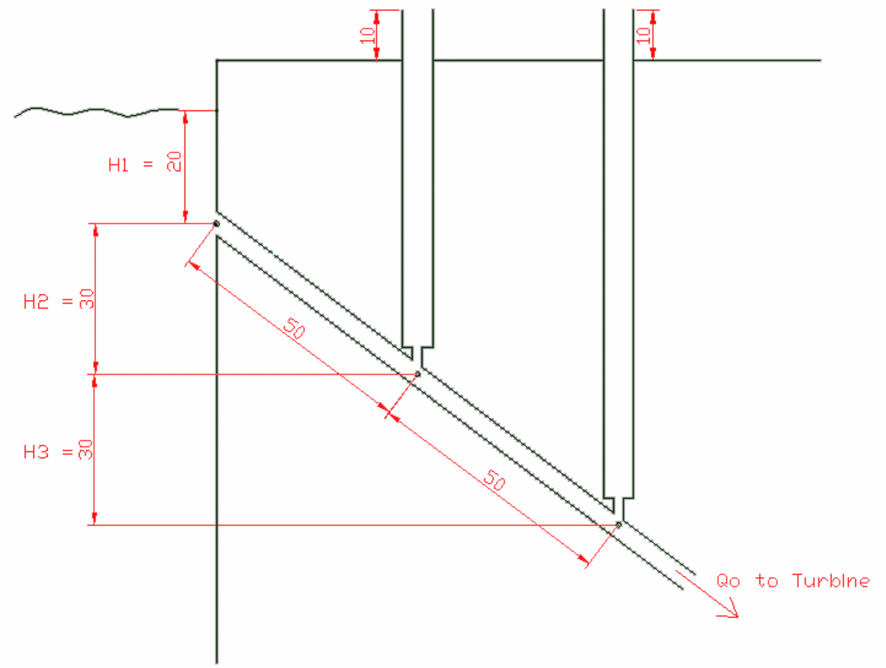


Fig 3-34 Hydraulic Power Plant System

DESIGN CRITERIA

Careful consideration must go into the modeling of this system when the water flow is cut to zero. This is another type of a nonlinear system. This problem can be solved one of a few different ways. Two of these methods will be discussed here.

1. This way is to break the problem up into three different systems. Then model each of the three systems individually but in order from A to C as described below. This can be done equally the same in Simulink or Matlab. In Simulink, three different models would be created. In Matlab, three different sets of files that make up the model representation would be created.

A. The first system being when all the initial conditions are zero and running until equilibrium has occurred.

B. The second system would be done using the ending values for the states from the first system for the initial conditions of the second system. This system would only cover when the flow is being cut from 1 cubic meter to zero in .1 seconds.

C. The third system would then use the ending values from the states in the second system for the initial conditions is the third system. This third and final system would then run until equilibrium has been established.

2. This way is to create a function or a set of conditional statements that will fully represent the nonlinearity for the flow source Qo. In Simulink, this can be done by creating an input function using the built in sources and adding them together. While, in Matlab this can be done by using a set of conditional statements.

The method that will be used to illustrate this example will be (2) from above. This will be demonstrated in both Simulink and in Matlab.

Seen below in *Fig. 3-35,* is the bond graph model for this system.

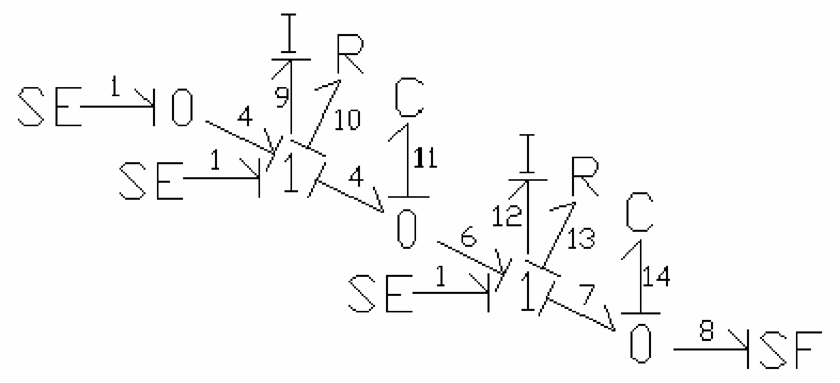
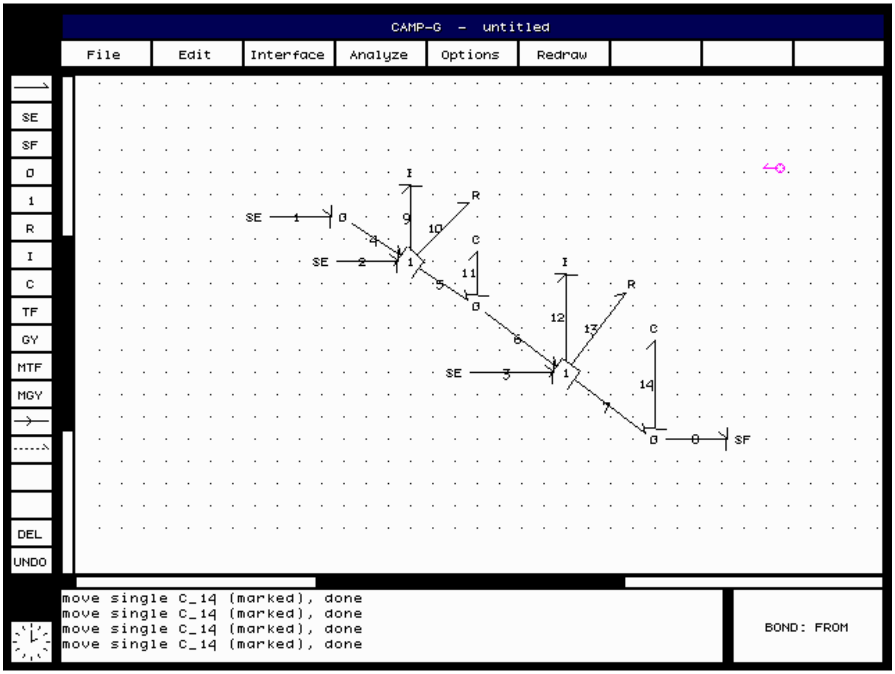


Fig 3-35 Hydraulic System Bond Graph Model

The bond graph from *Fig. 3-35*, above, is input into CAMPG as done in earlier methods and then interfaced with Matlab. This is seen in *Fig. 3-36*, below.



```
move single C_14 (marked), done
move single C_14 (marked), done
move single C_14 (marked), done
move single C_14 (marked), done
```

BOND: FROM

Fig. 3-36 CAMPG Power Plant Bond Graph Model

EQUATIONS

The equations for this system are as follows:

C=A/(g*rho)
I=(rho*L)/A
R=10^5 (H/m^2)/(m^3/sec)

deltaP1=rho*g*H1
deltaP2=rho*g*H2

CAMPG/Matlab Solution

Once the bond graph model was created in CAMPG, it was interfaced with Matlab as seen in *Fig. 3-36* from above. Using the CAMPGMOD.M and CAMPGEQU.M files that were created by CAMPG when interfaced with Matlab the simulation can be run once the physical parameters have been input into these two files.

The values for the physical elements were input into the files simply by editing them. The user can edit these files using the Matlab editor or "Notebook" or a similar program that will save the file with out any word processing formatting.

Using the method that was described in "2" above, *pg94*, the following flow source input function was created. This is an example to verify that the function created does what it is supposed to do. It is supposed to be constant at one cubic meter per second for a given time, enough time for the system to come to equilibrium. Then the function is supposed to go from one to zero cubic meters per second in .1 seconds. Finally the flow is supposed to remain constant at zero cubic meters per second indefinitely. Seen below in *Fig. 3-37* is the verification that the input function does what it is supposed to do. The listing for the M file that creates this is also shown below.

Listing of test.m

```
counter=1;
for t=0:01:200
   if t < 100
      SF8=1;
   elseif t >= 100 & t <= 100.1
      SF8=-10*t+1000;
   else
      SF8=0;
   end
SF(counter,:)=SF8 ;
counter=counter+1;
end
```

```
t=[0:01:200];
plot(t,SF,'r'), hold on
ylim([-.5 1.5])
xlabel('Time (seconds)')
ylabel('Volume Flow Rate (cfm)')
```

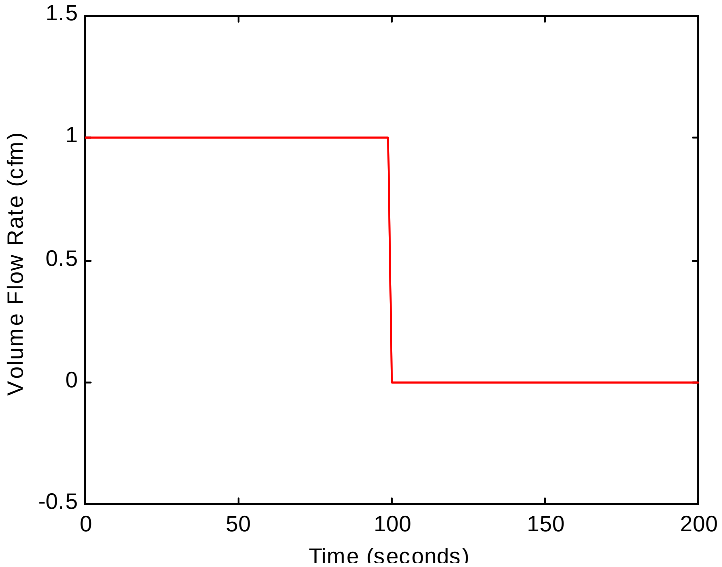


Fig 3-37 Nonlinear Function

After running the Simulink simulation with a few different values for the radius of the tanks, the following information in *Table 3* and *Table 4* was determined.

Radius	Max pressure in upper standpipe segment	Max pressure in lower standpipe segment	Max relative surge level in short surge tank	Max relative surge level in long surge tank
0.2 meters	154,770 Pa	103,600 Pa	58.25 meters	89.04 meters
0.3 meters	92,735 Pa	64,498 Pa	52.15 meters	83.00 meters
0.4 meters	63,208 Pa	46,689 Pa	50.26 meters	80.29 meters
0.5 meters	45,928 Pa	35,305 Pa	50.00 meters	80.29 meters

Table 3-3

Change in height	Max pressure in upper standpipe segment	Max pressure in lower standpipe segment	Max relative surge level in short surge tank	Max relative surge level in long surge tank
15 meters	53,160 Pa	64,500 Pa	37.15 meters	53.00 meters
30 meters	53,160 Pa	64,500 Pa	52.15 meters	83.00 meters
45 meters	53,160 Pa	64,500 Pa	Overflow	Overflow

Table 3-4

Height in Surge Tanks with Radius of .4 meters

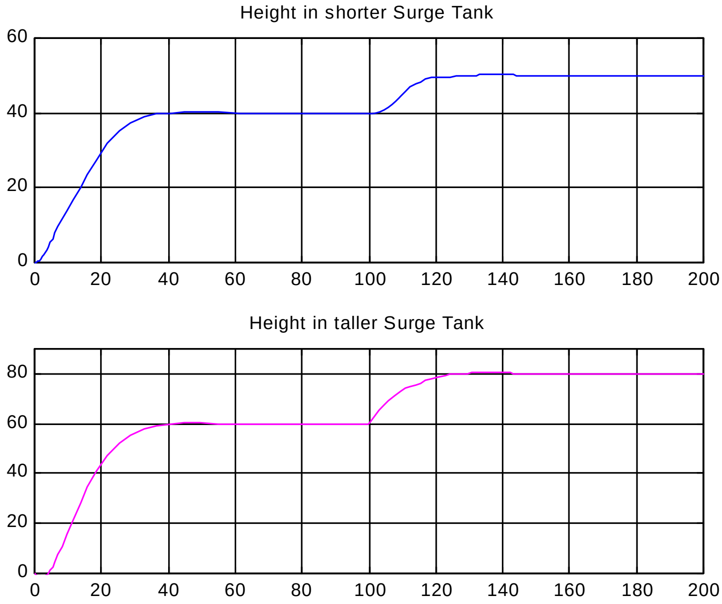
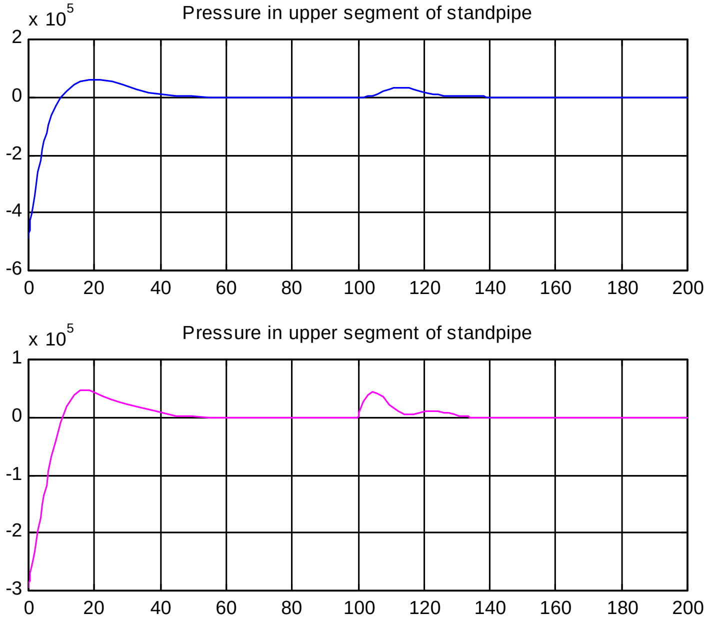


Fig 3-38 Height display

Pressure in Stand Pipes with Surge Tank Radius of .4 meters

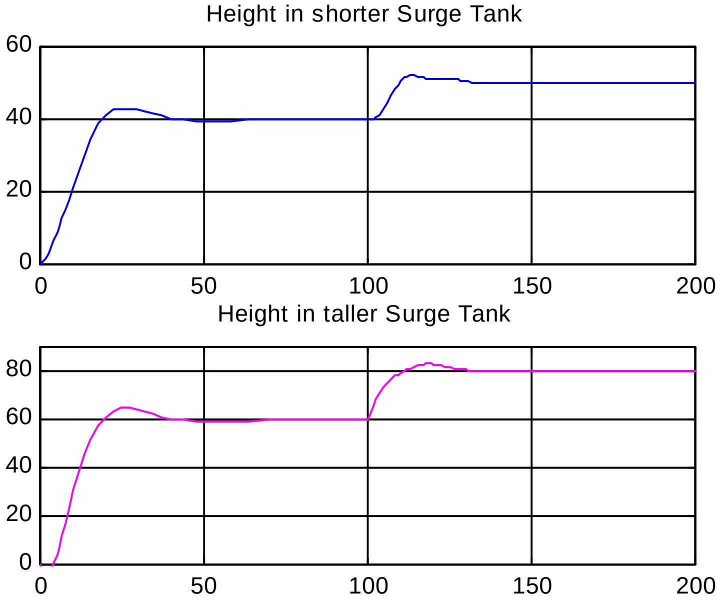
Fig 3-39
Pressure
Plots


Pressure in upper segment of standpipe

Pressure in upper segment of standpipe

Water Height in Surge Tanks with Radius of .3 meters

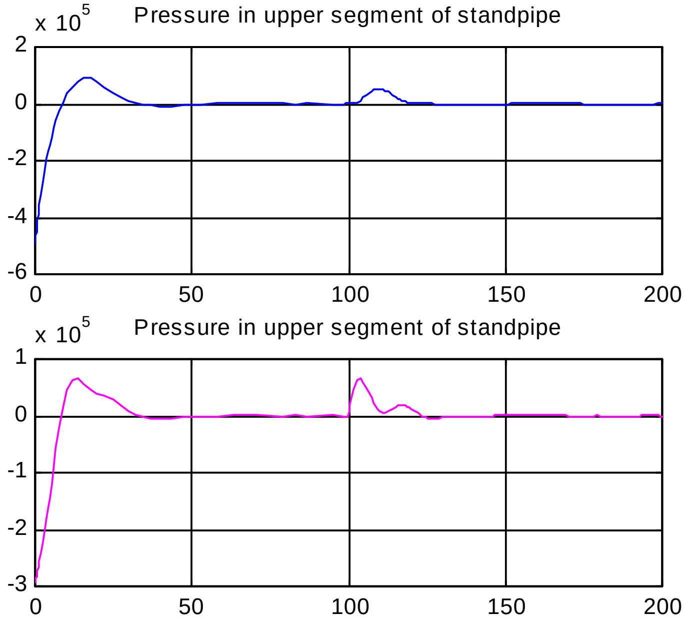
Fig 3-40
Water
Height


Height in shorter Surge Tank

Height in taller Surge Tank

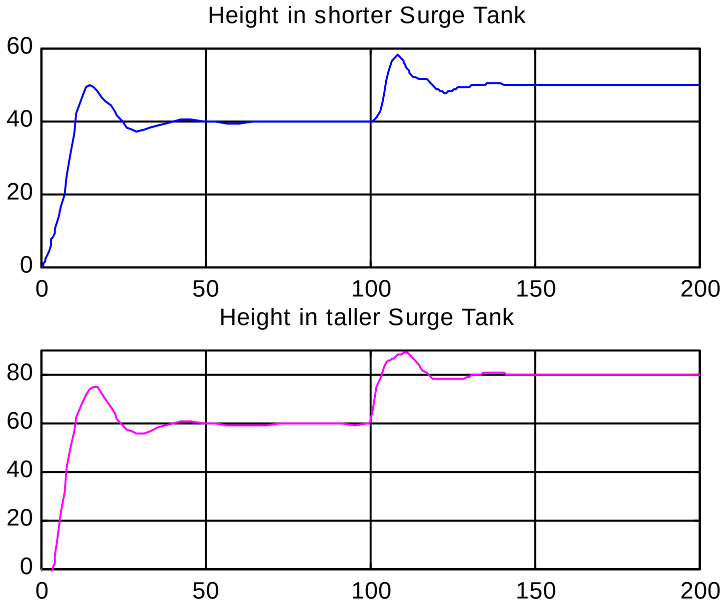
Pressure in Stand Pipes with Surge Tank Radius of .3 meters

Fig 3-41
Pressure
Plots



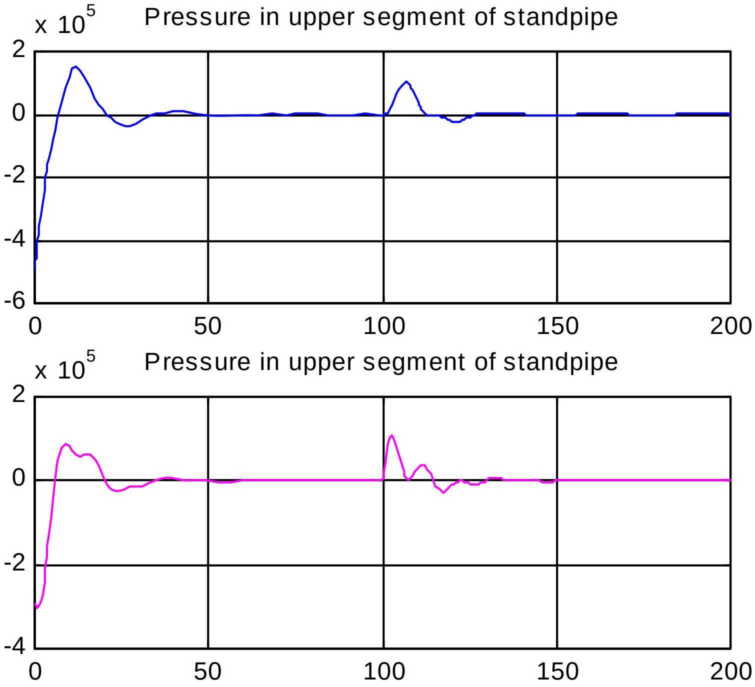
Water Height in Surge Tanks with Radius of .2 meters

Fig 3-42
Waterr
Height
Plots



Pressure in Stand Pipes with Surge Tank Radius of .2 meters

Fig 3-43
Pressure
Plots



Results

It seems as though .4 meters for a radius of the surge tanks would be pretty good. There is no over flow of the water and the pressures in the stand pipes are not very high. The data for .5 meters is better, but for all the additional water that would be required and the additional cost, it is not that good of an improvement. *Fig. 3-38 to Fig. 3-43* shows the water height in the surge tanks and the pressure in the stand pipes for radii of the surge tanks ranging from .2 to .4 meters.

Listing of Campgmod

```
 %    CAMPG/MATLAB - GENERATED MODEL DESCRIPTION:
 %      The following files have been generated
 %      campgmod.m  => m file containing model parameters
 %                    intial conditions, sources and
simulation controls
 %      campgequ.m  => m function containing the system
 %                    first order differential equations
 %      campgsym.m  => m file containing system matrices in
symbolic form
 %
 %    For simulation and control, edit these files
 %     Enter values for physical parameters, initial
 %     conditions,inputs and time controls
 %     in places where the ?? marks appear
 %     Standard generalized variables in Bond Graph notation
used.
 %
 %......CAMPGMOD.M - MATLAB MODEL INPUT FILE  ......
   clear all
   r=.4;
   A=pi*r^2;
 % ......  Initial conditions  ........
             P9IN= 0 ; P12IN= 0 ;
             Q11IN= 0 ; Q14IN= 0 ;
   initial = [Q11IN; Q14IN; P9IN; P12IN] ;
 % ......System Physical Parameters........
 global I9 R10 C11 I12 R13 C14  Efforts counter
             I9 = 1000*50/.1 ;  R10 = 100000 ;
             C11 = A/(1000*9.8) ;  I12 = 1000*50/.1 ;
             R13 = 100000 ;  C14 = A/(1000*9.8) ;
 % ...... External inputs se(t), sf(t) ......
   global SE1 SE2 SE3 SF8
             SE1 = 1000*9.8*20 ;
             SE2 = 1000*9.8*30 ;
             SE3 = 1000*9.8*30 ;
             %SF8 = ?? ;
 %..... Simulation Time Control .....
             t0= 0 ;   %  Initial Time
             tf= 200 ;   %  Final Time
             tspan= [t0 tf];
 % ......  Computer Simulation ......
 counter=1;
 %  Solution of system equations using Matlab "ode23" function
 %  The campgequ.m function contains the system differential
 %  equations in state variable form.
 %
 %  It returns the vector [t,p-q] where:
 %  t = time and p-q = vector of state variables
 %  For matlab version 4.2 use:
 %  [t,p_q] = ode23('campgequ',t0,tf,initial);
    status = odeset('outputfcn','esandfs');
    [t,p_q] = ode23('campgequ',tspan,initial,status);
 %          Q11= p_q(1) ; %          Q14= p_q(2) ;
 %          P9= p_q(3) ; %          P12= p_q(4) ;
 % State variables vector
   % p_q = [Q11; Q14; P9; P12] ;
 %
 % Sample Matlab structure for plotting simulation results
   figure(1)
   subplot (211),plot(t,p_q(:,1)/A,'b'),grid,axis([0 200 0
60])
   title('Height in shorter Surge Tank'),
   subplot (212),plot(t,p_q(:,2)/A,'m'),grid,axis([0 200 0
90])
   title('Height in taller Surge Tank')
   figure(2)
   subplot (211),plot(t,Efforts(:,1)*-1,'b'),grid
   title('Pressure in upper segment of standpipe')
   subplot (212),plot(t,Efforts(:,2)*-1,'m'),grid,zoom
   title('Pressure in upper segment of standpipe')
```

Note: Some of this file was cut out to save space.

Listing of Campgequ

```
   function p_qdot = campgequ(t,p_q)
 %  ...........campgequ.m   CAMPG/MATLAB function ...........
 %  System differential equations, state Vectors
 %
 global I9 R10 C11 I12 R13 C14 vect_out
 global SE1 SE2 SE3 SF8

   if t < 100
      SF8=1;
   elseif t >= 100 & t <= 100.1
      SF8=-10*t+1000;
   else
      SF8=0;
   end

 % System Differential Equations-First Order Form
 %...... Define State Variables ......
         Q11= p_q(1) ;         Q14= p_q(2) ;
         P9= p_q(3) ;          P12= p_q(4) ;
 % State variables vector
   % p_q = [Q11; Q14; P9; P12] ;
 %...... Define derivatives (dp,dq) and output variables (e,f)
......
         e1=SE1 ;                    e2=SE2 ;
         f9=P9/I9 ;                  e3=SE3 ;
         f12=P12/I12 ;               e4=e1 ;
         e11=Q11/C11 ;               f5=f9 ;
         e6=e11 ;                    f6=f12 ;
         e14=Q14/C14 ;               f7=f12 ;
         e8=e14 ;                    f8=SF8 ;
         f10=f9 ;                    f11=f5-f6 ;
         f13=f12 ;                   f14=f7-f8 ;
       dQ11=f11 ;                  dQ14=f14 ;
         f4=f9 ;                     f2=f9 ;
         f3=f12 ;                    e5=e11 ;
         e7=e14 ;                    e10=f10*R10 ;
         e13=f13*R13 ;               f1=f4 ;
         e9=e2+e4-e5-e10 ;           e12=e3+e6-e7-e13 ;
       dP9=e9 ;                    dP12=e12 ;

% ... Build vector of derivatives p_qdot(n)...
 %        p_qdot1) = dQ11 ; %        p_qdot2) = dQ14 ;
 %        p_qdot3) = dP9 ; %        p_qdot4) = dP12 ;
 % Derivatives vector
   p_qdot = [dQ11; dQ14; dP9; dP12] ;

 % ...  Define output vectors (efforts,flows)...

 % Sample structure for simulation outputs
 % effort_vector = [ e1 e8 e12 e4 ....]
 % flow_vector = [f1 f2 f3 f4 .....]
 % output_vector = [effort_vector flow_vector]
 %
```

```
% Example for graphical output.
% Plot e12 vs time (The third column of effort vector)
% subplot (211), plot (t,effort_vector(;,3),'y')
% Plot f10 vs time (The fourth column of flow vector)
% subplot (211), plot (t,flow_vector(;,4),'m'
% end
vect_out=[e9,e12];
```

Chapter 4

CAMPG and ACSL

4.1 Introduction

Using the CAMPG/ACSL system, algebraic and differential equations can be solved. CAMPG generates the system equations in source code form places them in an ACSL input file. This file is then completed using an editor to complete the system parameter specifications, nonlinear functions and ACSL library calls. The input file is passed to ACSL for dynamic analysis.

This chapter begins with a summary of some of ACSL's capabilities and the procedures required to successfully utilizing them. It then provides some examples of the CAMPG/ACSL system.

The Advanced Continuous Simulation Language (ACSL) is a program developed for modeling and evaluating the performance of continuous systems described by time dependent, linear or non-linear differential equations. These equations can be expressed as block diagrams (transfer functions), graphical representations (i.e. bond graphs), and of course algebraic expressions. The input format for the models allows the specification of the block diagram equations in any sequence. This means that as long as all variables are defined to the left of all equal signs, they could appear in any order. The computer will perform a logical variables sort prior to the computations.

Some of the most important features of the program are free form input, flexibility for plotting, many simulation-oriented operators; any FORTRAN function or user created subroutine may be used. It is this flexibility that allows a simulation language such ACSL to be a universal tool and describe just about any system nonlinearity or special function used to describe it.

Explicit Structure of a Simulation Model

A complete simulation model is stored in a disk file that can be used as ACSL input. It must include the physical parameters, initial conditions, differential equations and time control statements. These items are organized in a structured and organized way. An ACSL input file created by the user or by CAMPG contains these in the form of an explicit structure.

Groups of statements are organized in SECTIONS that start with a keyword and end with an END statement. These sections are **INITIAL, DYNAMIC, DERIVATIVE and TERMINAL**. These sections follow the explicit structure of ACSL input files. They are summarized below. A more extensive explanation can be found in the ACSL documentation.

```
PROGRAM
    INITIAL
                Statements performed before the run begins. State
    variables do not have the initial condition values at this point.
    Statements calculated only once prior to the start of a simulation.
    END
    DYNAMIC
        DERIVATIVE
                            Statements needed to calculate the
derivatives of each INTEG statement. The dynamic model.
Differential equations.
        END
    Statements executed every communication interval.
    END
    TERMINAL
    Statements executed when the termination condition TERMT
            becomes true.
     END
END
```

Statements describing the problem do not need to be sequentially ordered since the ACSL translator will perform a logical sort and generate code that will be compiled and executed sequentially.

ACSL processes the model input file in three stages. A **Translation**, a **Compilation** and a **Run Time** stage.   The translation processes the model file for the Fortran compiler. Once the model is compiled the linker produces an executable file that links the model and the ACSL libraries. This executable file runs and allows the user to enter the commands to calculate, display values and plot graphics output that is used in designing complete systems.

The explicit structure shown above is used to organize complex model descriptions. CAMPG generated models follow this structure.

Model Description Procedure

Each expression that describes a block diagram, differential equations or each algebraic expression representing the equations throughout the entire bond graph are placed in the ACSL input file in a form that follows FORTRAN assignment syntax. The lines of code can contain 80 characters. The first 72 columns are for program instructions and the rest for identification purposes. The expressions however follow free format description.

Statements can be written anywhere on the line (from column 1 to 72) in free format form, but it is a good practice to arrive at some standard to preserve the order and appearance of the text. More than one statement can be entered in one line.

Statements can be continued on the next line by adding three consecutive periods (...) at the end of the current line. The following are helpful considerations:

- Comments can be made by enclosing them in double quotes (").

- More than one statement can be placed on one line by separating them by a dollar sign ($).

- Blank lines can be inserted as desired.

- Text editor line numbers must not appear in the model definition program.

4.2 Running ACSL Using Differential Equations and Functional Blocks

Running a Basic ACSL Model
Let the mass of 0.02 kg be initially displaced 0.04m at time zero, held, and then released with an initial velocity equal to zero. Let the spring constant be 1.96N/m and the damper coefficient 0.05N-sec/m. It is desired to analyze the system response to an initial displacement or an external input. Single degree of freedom Oscillator

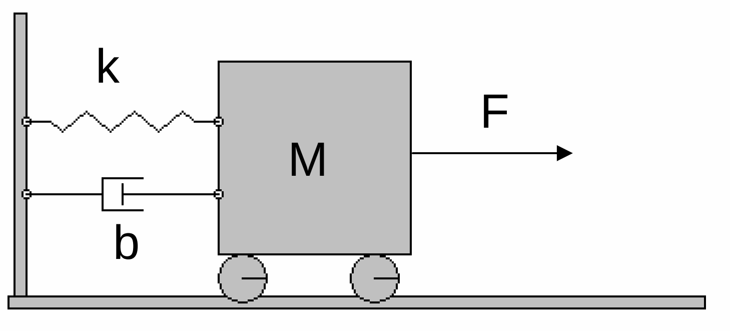


Fig 4-1 Single degree of Freedom System

Using the free body diagram the differential equation of motion can be found by applying Newton's Law. This is done by writing expressions for the sum of the external forces acting on the mass and setting it equal to the rate of change of linear momentum of the mass. The equation is:

$$m\ddot{x} + b\dot{x} + kx = 0$$

The objective is to find the solution for x(t). Double integration must be performed to find x(t). This is possible by calculating the second time derivative of **x** and then using the integration functions of ACSL twice to find the value of x(t).

The input model is generated and describes the equations in the form of source code. The initial parameters, initial conditions and the above description of the differential equation are entered using any text editor that will generate an ASCII file. The following ACSL input file was entered using the system editor:

```
PROGRAM OSCILLATOR              $" ACSL  INPUT FILE .."
   INITIAL
      CONSTANT M=0.02,K=1.96,B=0.05        $"<==Physical
                                                parameters"
      CONSTANT XDIN=0.0,XIN=0.04           $"<== Initial
                                                 conditions"
      CONSTANT TSTP=5.0                    $"<== Final
                                                   time"
      CINTERVAL CIN=0.05                   $"<== time step
                                                 interval"
   END  $ "OF INITIAL"
   DERIVATIVE
      F=0                                  $"<==     External
                                Input"
      "...... SYSTEM EQUATIONS  ......"
      XDD=(-B*XD-K*X+ F)/M   $"<== Second order derivative"
                                    " (acceleration)"
      XD=INTEG(XDD,XDIN)     $"<== first  order derivative"
                                 " (velocity)"
```

```
          X=INTEG(XD,XIN)           $"<== (displacement)"
          TERMT (T .GE. TSTP)       $"<== end condition"
END  $"OF DERIVATIVE"
END  $"OF PROGRAM"
```

To run the program after the model is stored on file enter:

```
ACSL  OSCILLATOR   (VAX/VMS systems)
ACSLCLG OSCILLATOR (IBM/PC)
```

The .CSL file type identifying a file, as an ACSL input file is not entered, the computer assumes the file name is "Oscillator.csl". The computer will respond:

```
START TRANSLATION          <== will appear on screen
START COMPILATION          <==  "    "   "    "
START LOAD                 <==  "    "   "    "

ACSL>                      <== ACSL run-time prompt.
```

Ready now for run-time instructions

```
ACSL>PREPAR T,XDD,XD,X     <== prepare (T, XDD, XD,
                               X) for plotting
ACSL>OUTPUT T,XDD,XD,X     <== prepare (T,XDD,XD,X)
                               for display
ACSL>START                 <== start simulation
...                        <== output written to screen
...                        <==   "       "   "   "
...                        <==   "       "   "   "
ACSL>PLOT XDD,XD,X         <== If using a Tektronics
                                graphics terminal
```

A plot of XDD,XD,X vs. T will be drawn on the screen.

```
ACSL>STOP                  <== stop ACSL execution
```

4.3 Running ACSL Using Bond Graph Modeling

Computer generated model
Shown below is the bond graph that represents the same simple oscillator discussed in the previous section. Using causality and power flow assignments, it is possible to generate the equations of the system and place them in the structure of an ACSL input file.

Bond Graph

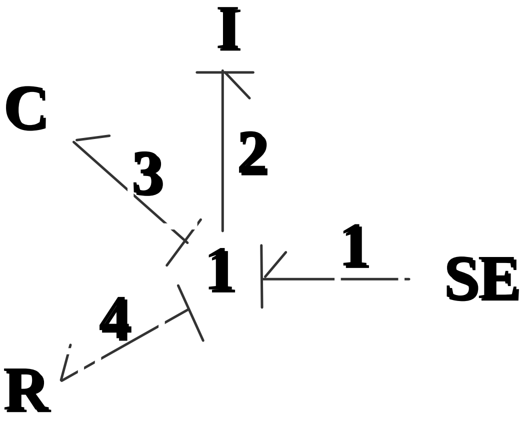


Fig. 4-2 Bond Graph of Single Degree of Freedom System

CAMPG can be used to create the ACSL an input file that has the same structure as the one created by the editor in the last example. To do this, run CAMPG and create the bond graph shown below following the guidelines presented in the modeling generation phase explained in Section 3 of this manual.

Once the bond graph model has been completed on the screen, select EXIT and the TO ACSL from the upper left corner of the CAMPG screen. The file CAMPSL.CSL will be created. Once parameter values have been entered it looks like this:

```
 PROGRAM  CAMPACSL  $" ACSL  INPUT FILE .."
    INITIAL
    CONSTANT   P2IN= 0.0  , Q3IN= 0.04                 $"Initial Conditions"
    CINTERVAL  CINT= 0.05                              $" Time Control T=time"
    CONSTANT   FINTIM= 5.0                             $" Final time"
    CONSTANT   I2=0.02, C3=.510204, R4=0.05       $"Physical parameters"
    END  $"OF INITIAL"
     DERIVATIVE
         SE1 = 0.          $".. EXTERNAL INPUT SE=F(T), SF=F(T)"
                             "...... SYSTEM EQUATIONS  ......"
          e1=SE1                 $   f1=f2
          e2=e1-e3-e4       $   f2=P2/I2
          e3=Q3/C3          $   f3=f2
          e4=f4*R4          $   f4=f2
          dP2=e2                 $   dQ3=f3
         "...... STATE VARIABLES ......"
         P2= INTEG (dP2,P2IN )                         $"Displacement"
         Q3= INTEG (dQ3,Q3IN )                         $"Momentum"
         TERMT (T.GE.FINTIM)                           $"Terminate Condition"
      END  $"OF DERIVATIVE"
   END  $"OF PROGRAM"
```

The individual equations form a close form set of differential equations in state variable form and can be verified using the causality and power flow of the bond graph. This file can be submitted for simulation using ACSL following the procedure outline in the previous section.

4.4 Different Ways to Execute the CAMPG/ACSL System

The menu explained in section 4.3 offers the user selections to translate, compile and run an ACSL model under CAMPG. There are three ways to start the CAMPG/ACSL model generation and execution files.

GENERATE A MODEL FOR FIRST TIME. -
A bond graph model is to be described to the computer and an ACSL input file is to be generated from scratch. Enter the command:

```
CAMPG
```

This invokes the CAMPG software package and allows the user to enter the descriptions of the simulation model using CAMPG graphic capabilities, menus and instructions.

Once the bond graph is complete, CAMPG will prompt the user with a menu to select the appropriate actions. It will automatically link with an editor for the ACSL input file. Complete the model description by inserting the physical parameter values, non-linearities, function calls, etc into the CAMPSL.CSL model file generated by CAMPG.

As soon as editing of the input file is complete CAMPG will display a menu that allows the user to continue with compilation and execution. Select the option to run ACSL with the input file. Automatically the ACSL translation, compilation and execution will take place. ACSL will then place the user at the ACSL prompt. Once at the ACSL prompt, the user can enter ACSL commands and start the simulation and graphical output of results. This is achieved by entering ACSL run time commands. A comprehensive explanation of these commands is presented in the ACSL reference manual.

MODEL FILE EXISTS ON DISK.-

If a file describing a simulation model has been created and is stored in a disk file, you may execute ACSL using that file by entering:

ACSLCLG filename

The system will respond with several messages indicating that the model is being processed in the following stages:

A - TRANSLATION	A translator converts the ACSL input file into code.
B - COMPILATION	The FORTRAN compiler uses this code to generate an object code.
C - LINKING	The system LINKER joins the system libraries and produces an executable file.
D - EXECUTION	The executable file runs the simulation.

If the user wants to run ACSL with and existing CAMPSL.CSL input file, simply enter the command:

ACSLCLG CAMPSL

EXECUTABLE FILE OF MODEL EXISTS ON DISK:

A model that has been simulated with parameter values can be studied further without having to recompile or link. The reason for this is that during the TRANSLATION, COMPILATION and LINKING stages, an EXECUTABLE file with the same name and .EXE file type is generated and written to the default disk drive. This file is an executable version of the user's model. For this reason it can be called and executed as any other executable file.

For example if the ACSL system was called with the command ACSLCLG MODEL, right before the system displays the ACSL prompt, the computer generated a file called MODEL.EXE. Therefore in order to run it without compiling it again, just enter the name of the file as MODEL and the computer will display the ACSL> prompt. At this point any ACSL run time command could be used.

SAVING THE MODEL FILES.
Once a simulation has been done, new modifications to the input file may be necessary and then the translation and compilation process will have to take place again. When running ACSL with a model file CAMPSL.CSL that was originally generated by CAMPG and then modified, it is suggested that the user changes the name of this file so that if he runs CAMPG again, the new model won't override the old modified and edited CAMPSL.CSL file. CAMPG has a safeguard against this problem. It will save the last CAMPSL.CSL file on the file CAMPSL.OLD.

4. 5 Useful Run Time Commands used with CAMPG/ACSL

The user may run a simulation problem once an ACSL input file has been generated and parameters values have been specified. When the ACSL> prompt appears, the user is in the ACSL program. There are several things to consider prior to the start of the simulation. First, a decision needs to be made by the user as to which variables are to be observed or plotted as the simulation takes place.

Establishing a variable list is accomplished with the PREPAR command. For example:

```
ACSL> PREPAR T,Q2,F3,E3
```

This command, will tell ACSL to save the values of time (T), displacement (Q2), velocity (F3), and force (E3). These variables are calculated and could be plotted later. Place the independent variable usually time (T) first because ACSL uses this information in the plotting routine to define the X-axis.

If an output listing of values of any variable is to be displayed as the simulation goes on, use the OUTPUT command followed by the list of variables.

For Example:

```
ACSL> OUTPUT T,Q2,F3,E3.
```

This requests ACSL to display the numerical values of these variables on the screen and write them to the ACSL output data file.

The simulation will start with the command:

```
ACSL> START
```

Once the simulation and all requested calculations have been performed, ACSL will come back with the prompt:

```
ACSL>
```

RUNTIME CHANGES TO PHYSICAL PARAMETER VALUES

Changes to the physical parameter values can be made at runtime without the need to edit again the input file. For example to change the value of the mass M or any constant value during simulation, use the command:

```
ACSL> SET M=0.06
```

This changes the value of the mass without having to go through the editing of the input file or he whole translation and compilation procedure again. The next time the START command executes the simulation again M will be 0.06 until changed again. The source file that describes the model is not modified.

ACSL needs to perform the simulation with the new values again and calculate the design variables that are under study. In order to do this enter the command:

ACSL> START

This process is useful when trying to alter variables to generate and optimum design. It is important to notice however that it is possible to change ONLY the variables defined with the CONSTANT definition. In order to change the values of these parameters, the runtime SET command is used. However, if it is used on a variable that has not been defined as a constant, the computer will recalculate values based on the original ACSL input file definition. For this reasons any parameter that we want to vary at runtime, needs to be defined as a CONSTANT. Otherwise the system simply will ignore the change. The following example shows the placement and syntax of the CONSTANT command in the ACSL input file generated by CAMPG.

```
PROGRAM  CAMPACSL     $" ACSL  INPUT FILE .."
INITIAL
     CINTERVAL  CINT= 0.05               $" Time Control T=time"
     CONSTANT   FINTIM= 5.0 , I2=0,02, C3=.510204, ...
      R4=0.05, P2IN=0.0, Q3IN=0.04
                                " Final time, Physical parameters, initial
                                  periods continue definition of constants"
END  $"OF INITIAL"
DERIVATIVE
     SE1 = 0.            $".. EXTERNAL INPUT SE=F(T), SF=F(T)"
     "...... SYSTEM EQUATIONS  ......"
               e1=SE1                $   f1=f2
```

```
                    e2=e1-e3-e4         $  f2=P2/I2
                    e3=Q3/C3            $  f3=f2
                    e4=f4*R4            $  f4=f2
                    dP2=e2                 $  dQ3=f3
               "...... STATE VARIABLES ......"
               P2= INTEG (dP2,P2IN )                         $"Displacement"
               Q3= INTEG (dQ3,Q3IN )                         $"Momentum"
               TERMT (T.GE.FINTIM)                           $"Terminate Condition"
            END  $"OF DERIVATIVE"
            END  $"OF PROGRAM"
```

Here the CONSTANT statement is used to define all the parameters. The (...) three periods are used to express continuation of the definition (in this case CONSTANT) defined in the previous line.

GENERATION OF ACSL PLOTS

The ACSL prompt appears again after the start command is done executing the simulation. The user may now tell ACSL to create some plots of the variables listed in the PREPAR command. ACSL is capable of plotting line plots, printer plots, and strip plots. Plots are generated using the PLOT command.

The PLOT command is entered followed by the variable or variables you want to plot. ACSL assumes that the first variable listed in the PREPAR statement is the independent variable (usually time), which is placed on the X-axis. The variables that follow are interpreted to be the dependent variables to be plotted as a function of the independent variable (time).

For example, if the user wants to plot Q2 as a function of time then enter the command:

ACSL> PLOT Q2

This command will generate a plot of Q2 versus time with automatic scaling assuming time was the first variable in the PREPAR list.

Labels, colors, scaling, and much more can be added to these plots with the appropriate syntax of the options of the PLOT command. Several of these options are explored in the following section and others are listed in the ACSL manual.

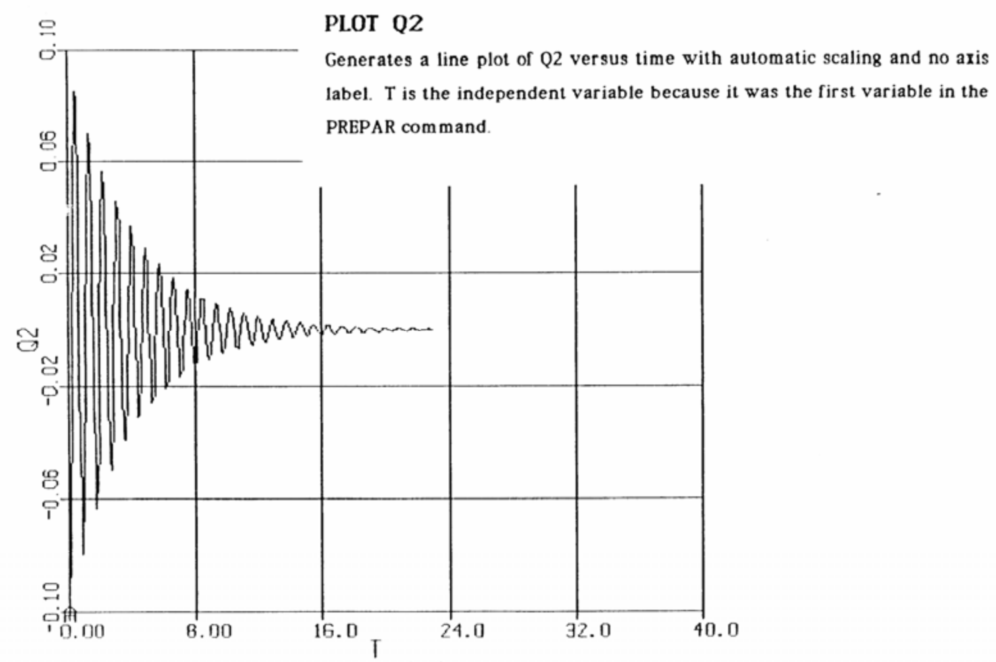
PLOT CONTROL OPTIONS

The plot command has many options that allow the user to compare variables in the bond graph, plot them separately, change the scale, color, type of lines etc. A summary of these options include:

"XHI"=TSTP	Specifies the time limit for the values to be plotted. The time in turn specifies the "length" on the X-axis.
"XTAG"="(SEC)"	Prints the tag (SEC) on the X-axis
"LO"	Lower limit for the Y-axis
"HI"	Higher limit for the Y-axis
"TYPE"=n	Specifies color for line plots
STRPLT	Requests strip plots
GRDSPL	Draws lines from each tick mark on the axes
YASSPL	Separation between strip plots
XTICPL	X-axis tick increment in inches for line plots.
XTISPL	Also X-axis tick increment but for strip plots
XINCPL	X-axis length in inches for line plots
XINSPL	Same but for strip plots

The values of the last five parameters may be different for each type of terminal and the printer attached to them, reference the ACSL manual for more details and more options.

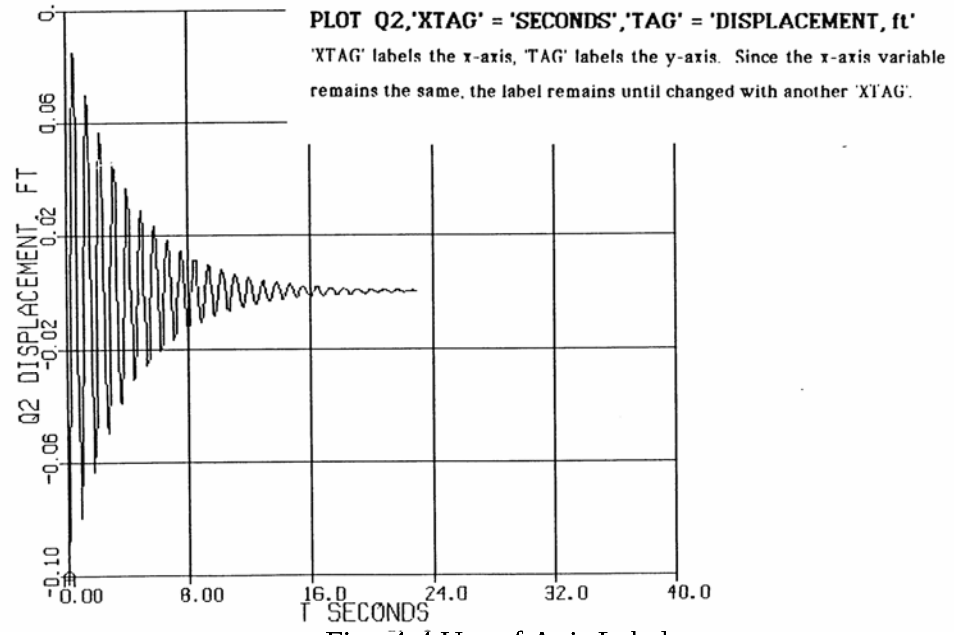
The following examples illustrate some of the plotting capabilities available to the user on ACSL. Some of the commands are applicable to all subsequent plots and the user should note this with some practice. Each plot shows the command that was used to generate it.



PLOT Q2

Generates a line plot of Q2 versus time with automatic scaling and no axis label. T is the independent variable because it was the first variable in the PREPAR command.

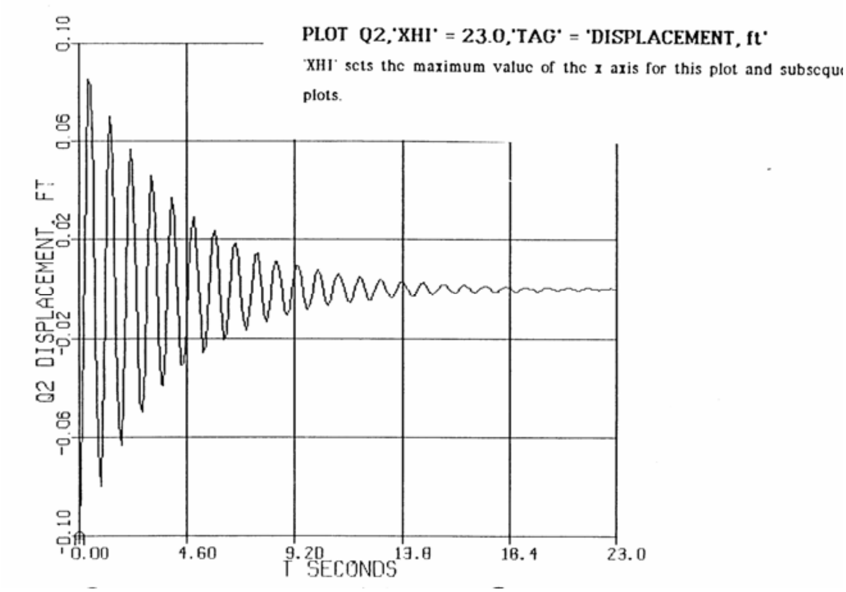
Fig. 4-3 - Shows the default plot command with automatic scaling and no axis labels.



PLOT Q2,'XTAG' = 'SECONDS','TAG' = 'DISPLACEMENT, ft'

'XTAG' labels the x-axis, 'TAG' labels the y-axis. Since the x-axis variable remains the same, the label remains until changed with another 'XTAG'.

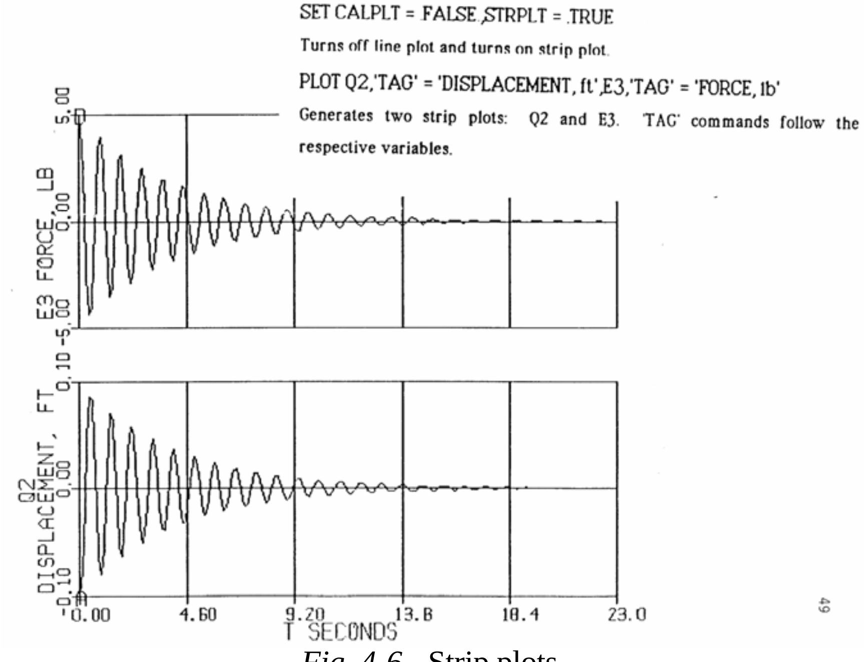
Fig. 4-4 Use of Axis Labels



```
PLOT Q2,'XHI' = 23.0,'TAG' = 'DISPLACEMENT, ft'
```

'XHI' sets the maximum value of the x axis for this plot and subsequ plots.

Fig. 4-5 - Time control of x-axis and scaling.



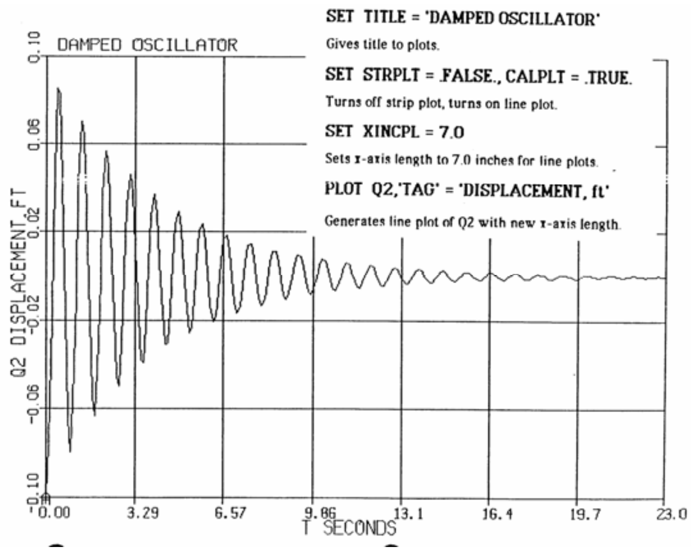
```
SET CALPLT = FALSE ,STRPLT = .TRUE
```

Turns off line plot and turns on strip plot.

```
PLOT Q2,'TAG' = 'DISPLACEMENT, ft',E3,'TAG' = 'FORCE, lb'
```

Generates two strip plots: Q2 and E3. 'TAG' commands follow the respective variables.

Fig. 4-6 - Strip plots.



SET TITLE = 'DAMPED OSCILLATOR'

Gives title to plots.

SET STRPLT = .FALSE., CALPLT = .TRUE.

Turns off strip plot, turns on line plot.

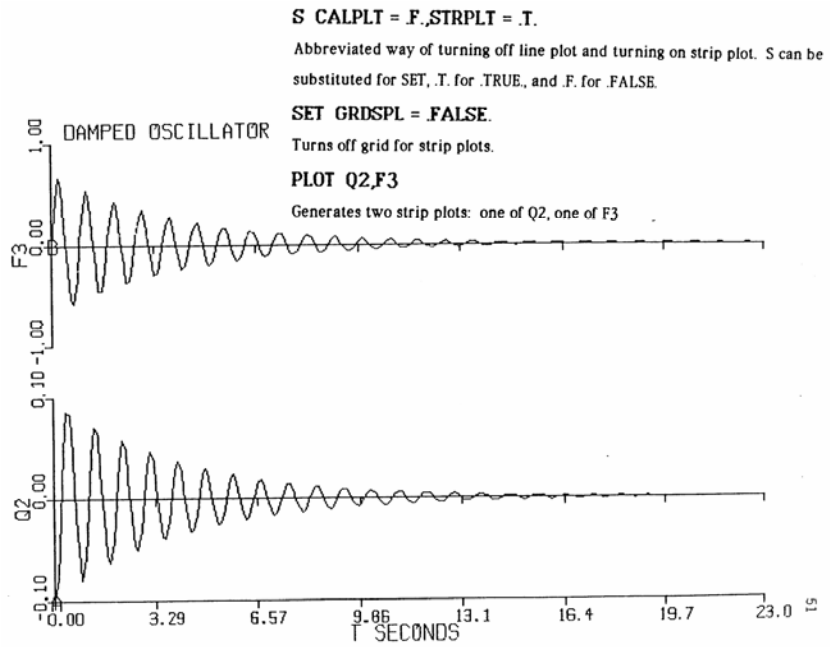
SET XINCPL = 7.0

Sets x-axis length to 7.0 inches for line plots.

PLOT Q2,'TAG' = 'DISPLACEMENT, ft'

Generates line plot of Q2 with new x-axis length.

Fig. 4-7 - Plot size control.



S CALPLT = .F.,STRPLT = .T.

Abbreviated way of turning off line plot and turning on strip plot. S can be substituted for SET, .T. for .TRUE., and .F. for .FALSE.

SET GRDSPL = .FALSE.

Turns off grid for strip plots.

PLOT Q2,F3

Generates two strip plots: one of Q2, one of F3

Fig. 4-8 - Plot Grid control and number of strip plots.

4.6 Setup Files

It is possible to speed up the simulation and the graphical result using setup files. These files store a set of ACSL runtime commands in a file. A setup file is a working file during the simulation and the ACSL system knows to execute the commands from this file. The SET CMD command is used to control and set the ACSL input commands to this file or to the computer terminal. The setup file stores the ACSL commands in groups starting with a label and the PROCEED keyword. A set of command or a set of commands can be executed if the user enters the label that heads up the list of commands and ends with an END.

Using the SETUP files saves a great deal of time not only by saving the time to enter the commands but the execution of groups of commands. Commands that are on the SETUP file don't need to be typed again at the ACSL prompt. These files are known also as SETUP files or COMMAND files. These files provide an easy way to do several simulations study different cases and enter several options of the ACSL commands that otherwise will be too long to do at the ACSL prompt.

This is a practical idea; a SETUP FILE is created using the editor. This file defines the run-time commands for a simulation. The ACSL system reads this file by passing control of the ACSL input to this file. In the IBM/PC this is accomplished by naming the SETUP file with the same name as your input file and the extension .CMD. In order to transfer control of the input command to this SETUP file. The SET command is used as follow:

```
ACSL>SET CMD=10     (IBM//PC)
```

Unit 10 is defined as the logical unit identified with the .CMD file. The above command allows the commands in the setup file to be available for execution.

Other computers have a similar way of associating the SETUP file to the simulation. For a VAX computer under VMS for example the procedure is as follow:

- At the VAX prompt $> and before ACSL is called enter:

  ```
  $> ASSIGN SETUP.DAT FOR010
  ```

  This command identifies Unit 10 with the SETUP.DAT file.

- Start ACSL. For example use file OSCILLATOR.CSL

  ```
  $> ACSL OSCILLATOR

  ...  <== translation, compilation loading steps
  ...  <==    "             "       "   "    "
  ...  <==    "             "       "   "    "
  ```

- At the ACSL prompt "ACSL>" enter the following commands:

  ```
  ACSL>SET CMD=10      <==   connects unit 10 to
                             SETUP.DAT file. The setup
                             file could have been named
                             OSCILLATOR.CMD
                             following the convention for
                             the IBM/PC.

  ACSL>START           <==   start calculation
                             If the file contains this
                             command it is not necessary
                             to issue it here.

  ...                  <==   numerical output
  ...                  <==      "       "
  ...                  <==      "       "
  ```

```
ACSL > A                <==   invokes procedure to plot
                           forces see file below.
ACSL > B                <==   invokes procedure to plot
                              velocities. See file below.
```

The last two commands contain just the letter A and the letter B. This means execute the commands contained in the SETUP file that are describer under the procedure A. The procedure A is defined by the keyword "PROCEED" and the label, which is this case, is the letter "A". Then execute the commands contained in the SETUP file under the procedure B. These procedures are displayed in the SETUP file example shown below. For example, the PREPAR and OUTPUT statements and the different PLOT statements can be generated by using a SETUP file like the one below:

```
SET TITLE= "DAMPED OSCILLATOR"
PREPAR T,E1,E2,E3,F3,Q3
OUTPUT T,E1,E2,E3,F3,Q3
SET TCWPRN=72
START
PROCED A
    SET TITLE= "SPRING, DAMPER AND MASS FORCES"
    PLOT E1,E2,E3
END
PROCED B
    SET TITLE= "VELOCITY OF THE MASS"
    PLOT F3
END
PROCED C
    SET TITLE= "DISPLACEMENT OF THE MASS"
    PLOT Q3
END
SET CALPLT=.TRUE.,PRNPLT=.FALSE.,PLT=6
SET CMD=DIS
```

This SETUP file sets up the initial TITLE, which will appear in the respective plots. The commands in this example do the following:

PREPAR Prepares the calculation tables for plotting.

OUTPUT Requests a display of the calculated values on the screen as the simulation executes. If the output is large and a listing on the screen would be too long and the output therefore is not desired, the command can be suppressed if previously set. Use OUTPUT "CLEAR" and there will be no output to the screen. A, B and C define different procedures specifying different plots.

TCWPRN Forces three-column output width (72 characters per line).

CALPLT Implies a line plot (practical while using a graphics terminal.

PRNPLT=.FALSE. Turns off printer plots. This is particularly useful if the user is not using a graphics terminal.

PLT Directs the plot to the screen.

The procedures A,B, C can be executed just by entering one of those letters in which case they act as labels or names for that procedure defined in the SETUP file and delimited by each label (A,B,C, ..) and an END statement. Note that other names besides A,B,C could be used as labels. The user may choose to name the procedures with any name. The name of those procedures are entered at runtime to execute the commands that are within them.

4.7 Important ACSL Features

ACSL contains many useful features and commands which assist the user in the analysis and simulation of a dynamic system. A summary of these follows. A more detailed explanation of the features, can be found in the ACSL manual.

PROCEDURAL

FORM: PROCEDURAL(output list = input list)

where:
output list = v1, v2,..., vn
input list = e1, e2,..., en

"v_i" are non subscripted variable names while "e_i" may be variables or expressions. The PROCEDURAL header must be paired with a matching END statement.

The PROCEDURAL key word defines the beginning of a block of PROCEDURAL code to be executed in the sequence given; i.e., the code within the PROCEDURAL block is not sorted by the ACSL translator.

The following two examples use the simple suspension system to illustrate the use of the procedural. Here, the objective is to define a set of FORTRAN statements to be executed in sequence and define the input road conditions (SF1). The plots that follow the input files, show the input function and the displacement of the vehicle DELTA X (Q4). Note that each procedural needs an END statement.

The first example, Fig 3-9 shows a file of a simple suspension system. It defines the input function (SF1) at time 5 sec, as zero if time is greater than 5 sec, and again with a value of .5 at time equal 7 sec. Fig 4-10 shows a plot of the input function (SF1) and the resulting motion of the mass (m) plotted as (Q4) vs time. It clearly demonstrates the discontinuities defined in this function.

The second example, Fig 4-11, uses the same system by defines SF1 as a function of time (T) to be 0, to be a harmonic function after 5 sec and zero again after 10 sec. This illustrates that nonlinear discontinuous functions can be defined with a procedural and work with the bond graph structure and equations generated by CAMPG. The dynamic graphical display of (SF1) and the response (Q4) are shown in Fig 3-12 The same methods can be applied to define the nonlinear behavior or parameter values of C, I, R, TF and GY elements. Control signals and activated bonds can be also defined this way.

It is this capability that links the technology of bond graph modeling with a general purpose, open ended simulation systems such as ACSL and other simulation languages. This provides the system analyst with a tool for simulation of a wide range of multi energy non linear systems.

```
PROGRAM  CAMPACSL          $ "Demonstration of Procedural"
   INITIAL
   "...... INITIAL CONDITIONS ......"
      CONSTANT   P2IN= 0.0  , Q4IN= 0.0
   "..... TIME CONTROL (T=TIME)....."
      CINTERVAL  CINT= 0.1
      CONSTANT   FINTIM=  15  $  " SYSTEM PHYSICAL PARAMETERS "
      CONSTANT I2 = 1.5           $  C4 = 1/39.478
      CONSTANT R5 = 7.5
   END  $"OF INITIAL"
   DYNAMIC
      DERIVATIVE
                  " Use of Procedural allows a set of FORTRAN statements ...
                  to define the input (SF1).  The roadway input changes as if...
                  the driver hit some big speed bumps.  "
         PROCEDURAL (SF1=T)
            SF1 =0.
            IF(T.EQ.5) SF1 = 0.2
            IF(T.GT.T) SF1 = 0.
            IF(T.EQ.7) SF1 = 0.5
            IF(T.GT.7) SF1 = 0.
```

```
                    END
            "...... SYSTEM EQUATIONS  ......"
                    e1=e3            $  f1=SF1
                    e2=e3            $  f2=P2/I2
                    e3=e4+e5         $  f3=f1-f2
                    e4=Q4/C4         $  f4=f3
                    e5=f5*R5         $  f5=f3
                    dP2=e2           $  dQ4=f4
               "...... STATE VARIABLES ......"
                    P2= INTEG (dP2,P2IN )
                    Q4= INTEG (dQ4,Q4IN )
               "TEMINATE CONDITIONS"
                    TERMT (T.GE.FINTIM)
                              END  $"OF DERIVATIVE"
       END  $"OF DYNAMIC"
  END  $"OF PROGRAM"
```

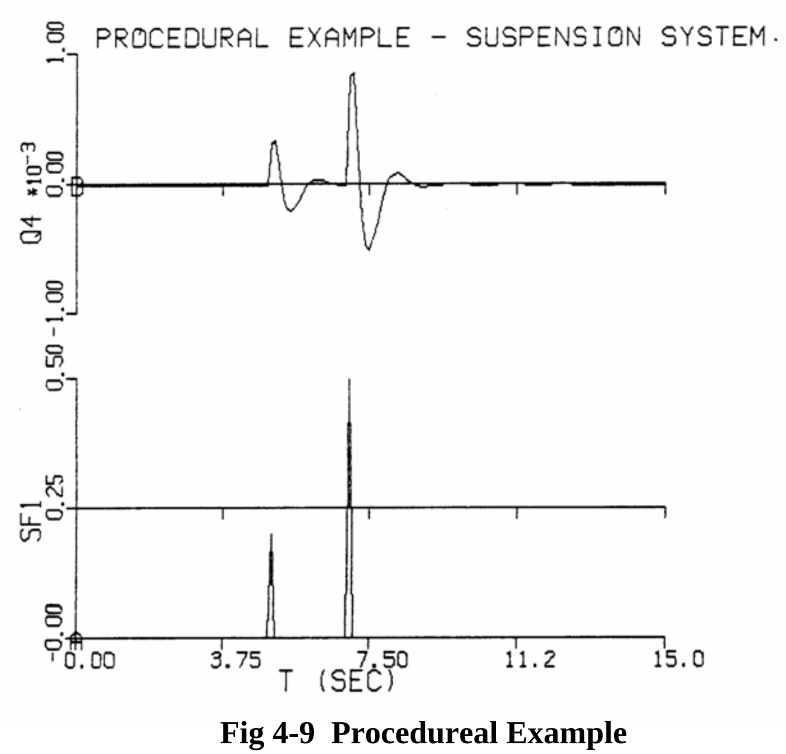


Fig 4-9 Procedureal Example

Shown below is a portion of a new CAMPG/ACSL input file that defines the procedural for a different input function in this case a harmonic with time controls at the onset and at the end.

```
PROGRAM  CAMPACSL               $ "Demonstration of Procedural"
..
.
.
    DYNAMIC
        DERIVATIVE

              " Use of Procedural allows a set of FORTRAN statements ...
                to define the input (SF1).  The roadway input changes from...
                level to harmonic and back to level. "


            PROCEDURAL (SF1=T)
                SF1 =0.
                IF(T.GT.5)  SF1 = -6.283 * COS(6.283 * T)
                IF(T.GE.10) SF1 = 0.0
            END
        "...... SYSTEM EQUATIONS  ......"
                e1=e3          $  f1=SF1
                .
                .
                .               .
                .
                            END  $"OF DERIVATIVE"
    END  $"OF DYNAMIC"
END  $"OF PROGRAM"
```

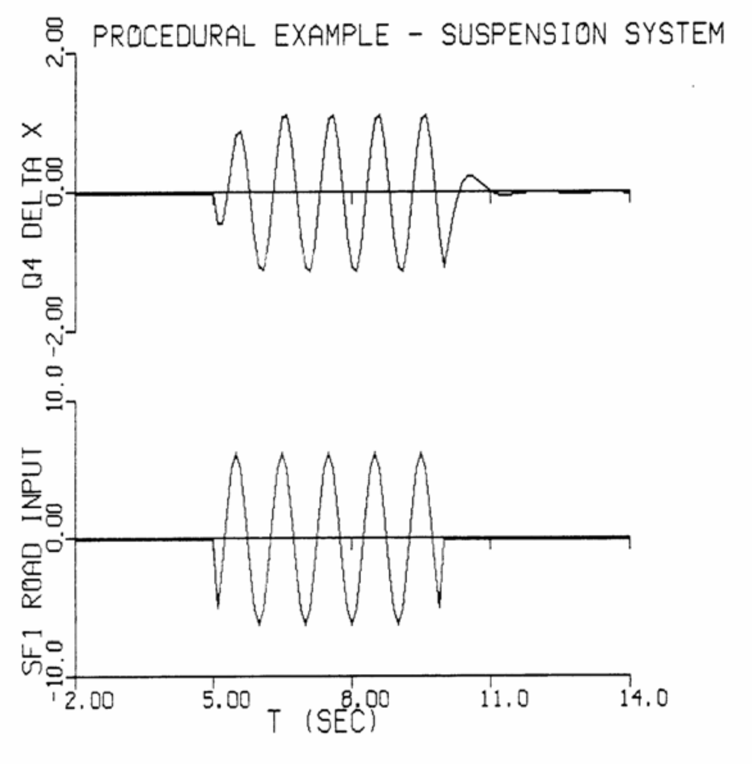


Fig. 4-10 Procedural Generated Display

EIGENVALUE ANALYSIS

ANALYZ command

```
FORM:ANALYZ

SUBCOMMAND:'TRIM'
           'EIGEN'
           'EIGVEC'
           'JACOB'
```

The ANALYZ command invokes the linear analysis capability of ACSL. This is used to evaluate the Jacobian, trim the state variables to null the rates, and calculate eigenvalues and their associated eigenvectors.

The 'TRIM' sub-command transfers the initial conditions to the state variables, computes the JACOBIAN, and then, using Newton iteration and the steepest descent step, adjusts the state variables until the derivatives go to zero.

The sub-command 'EIGEN' calculates the Jacobian and then evaluates and lists the complex eigenvalues and optionally the eigenvectors. If used, the 'EIGVEC' sub-command should precede 'EIGEN' as it determines whether eigenvectors are to be calculated. Once set, 'EIGVEC' stays defined until explicitly changed.

The sub-command 'JACOB' calculates the Jacobian about the current point in state space by numerical perturbation. The result is then printed out as a large matrix. The ACSL (Ref 4) manual contains a complete listing of ACSL operators and other run-time commands.

FORTRAN SUBROUTINES

Any user-defined FORTRAN function or subroutine may be used in the simulation input file by including it following the END statement that matches the PROGRAM statement. The translator looks for the following:

```
REAL FUNCTION...
INTEGER FUNCTION...
LOGICAL FUNCTION...
SUBROUTINE...
FUNCTION...
PROGRAM...
```

Once one of these key words is found, it assumes all the rest of the lines in the model definition section are to be passed directly to the FORTRAN compiler. The format of these statements is not changed in any way, so FORTRAN format must be followed exactly; i.e., start in column seven or beyond, etc.

4.8 CAMPG/ACSL Tutorial

The following is a summary of the steps that are to be taken to generate a bond graph model from scratch and end up with the final analysis results in the form of calculated values and plots that will allow the engineer to make design decisions.

1.- GENERATE THE BOND GRAPH - The bond graph model can be created right on the screen or transferred from a model drawn on paper. The technical references offer detailed explanation of the method and the methods for generating the bond graph models from real dynamic systems.

2.- CAMPG - The bond graph model is entered using the menu and the mouse. Section 3 describes this in detail. CAMPG is called by entering the command CAMPG and the user proceeds to draw the bond graph model. CAMPG will point out modeling problems using different colors and allowing the user to examine the system equations as the model is entered. There are clear indicators on the screen as to the status of the cursor and the actions that the program will take.

3.- GENERATE AN ACSL INPUT FILE - Once the model is completed on the screen and no modeling problems that will prevent the generation of a close form set of equations have been detected, the user will select the EXIT button. CAMPG will offer the choices to return to DOS or continue and interface CAMPG with a simulation language. If ACSL is the language of choice, then that button is selected and CAMPG will generate the input file CAMPSL.CSL containing all the necessary initial conditions variables, parameters, time controls and the system differential equations in first order form. This form is completely compatible with a state variable form of the system equations.

4.- ENTER PARAMETER VALUES - CAMPG will place the user in a position to edit the CAMPSL.CSL file that it generates. Now the user needs to enter the values of the initial conditions, time control, physical parameters, nonlinear equations, nonlinear functions, activated bond specifications, signals and any other description necessary to complete the model.

The INITIAL section contains definitions of the initial conditions, time control and physical parameters. The DERIVATIVE section needs specifications of the input functions. CAMPG generated the ACSL input file with ?? marks in the places where numerical values or functions definitions need to be specified to complete the model.

5.- RUN ACSL - The user runs ACSL using the CAMPSL.CSL as its input file. This file was completed in the previous step. The inputfile can have any other name that the user wants to use. Now the user is in a position to enter and take advantage of all the ACSL run time commands and simulation capabilities. The user can issue commands to simulate, display and plot the calculated values. The PREPAR, OUTPUT, START and PLOT commands are used for this purpose. Section 5.5 offers more information on this step.

6.- OPTIMIZE SIMULATION - Once familiar with the previous steps and confident to obtain results from ACSL, the user can proceed to optimize and speed up the simulation as well as run several different simulations on the model under study. This can be achieved by entering a series of runtime commands but it can be done quickly and avoiding mistakes by placing these commands in a SETUP file. This file can be linked to the ACSL simulation at runtime and ACSL will read and execute the commands in it. Several simulations can be done with different parameter values and conditions for executions as well as the great variety of plots that ACSL is capable of generating. The user may find more information about this on Section 5.6 and the ACSL reference manual.

4.9 Linear System Example - Vehicle Crash Test

PROBLEM:
The dummy in the figure shown below is driving his new VW-Rabbit into a wall !!. Will his shock absorbing bumper (k2,b2) and his seat belts (k1, b1) prevent him from hitting the windshield without breaking his collarbone?

DATA ON INJURIES (SAE Handbook)
Seat belts must be tested to 3000 lbs. (1.334 x 104) N
Chest can sustain a force of 1500 lbs distributed over 30 in^2.
Seat belt effective area = 30 in^2
Shoulder strap-seat belt combination = 60 in^2

PHYSICAL PARAMETERS
M= 1500 Kg, k_1= 1 x 10^4 N/m, b_1=500 N-s/m
m= 100 kg, k_2= 3 x 10^5 N/m, b_2=8 x 10^4 N-s/m

Physical System of Dummy in Car

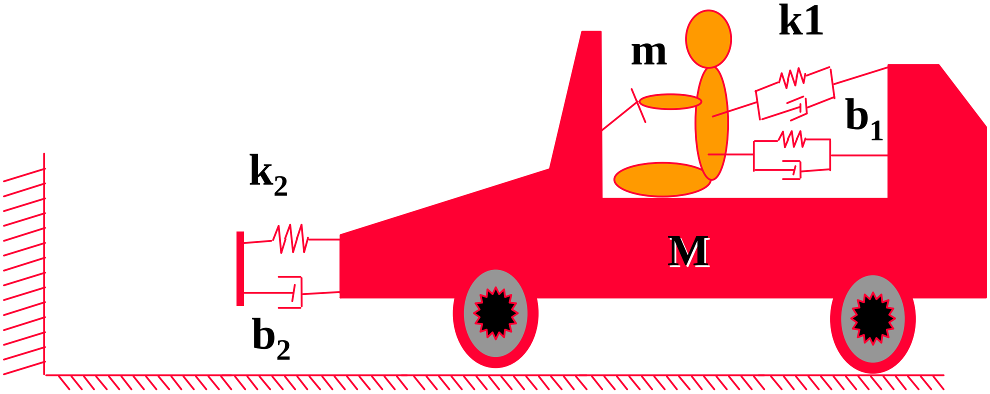


Fig. 4-11 Seat Belts Design

OBJECTIVES:

1. Generate an engineering model of a physical system.
2. Transform the engineering model of reality into a computer model for simulation using the Computer Aided Modeling Program (CAMPG).
3. Perform interactive simulation and generate numerical and graphical output using the Advanced Continuous Simulation Language (ACSL).
4. Interpret the results make design decisions and perform simulation of several models in an interactive way.

PROCEDURE FOR SOLUTION

1. Construct an engineering model of the crash test and consider only the time when the bumper is in contact with the wall. *Fig. 4-11*, seen above, shows the engineering model of the crash test.
2. Generate a bond graph model. *Fig. 4-12*, seen below, shows the bond graph model for this dynamic system.
3. Enter the Bond Graph description into the CAMPG program. *Fig. 4-13*, seen below, shows the CAMPG screen that was generated after entering the bond graph model.

Bond Graph Model

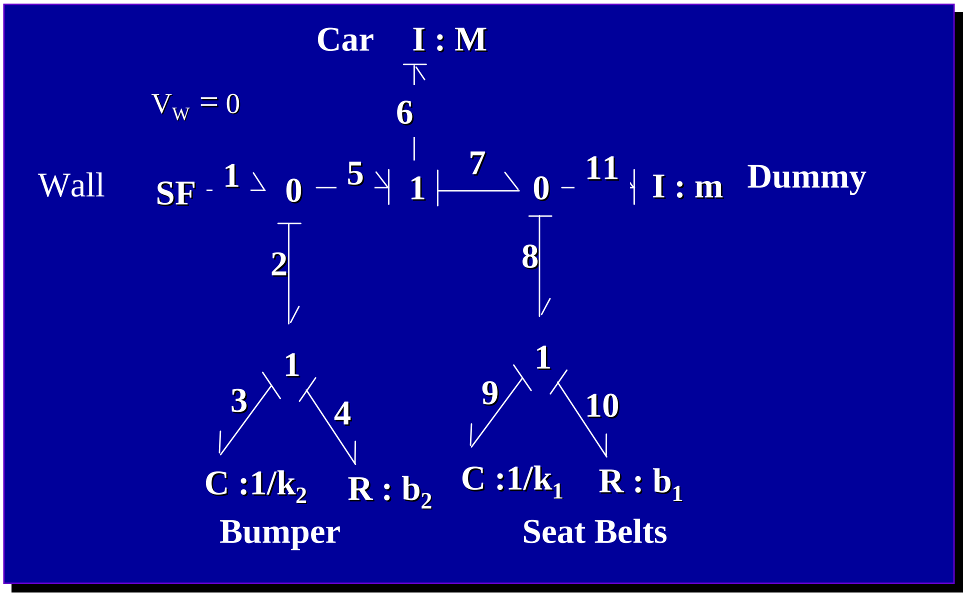
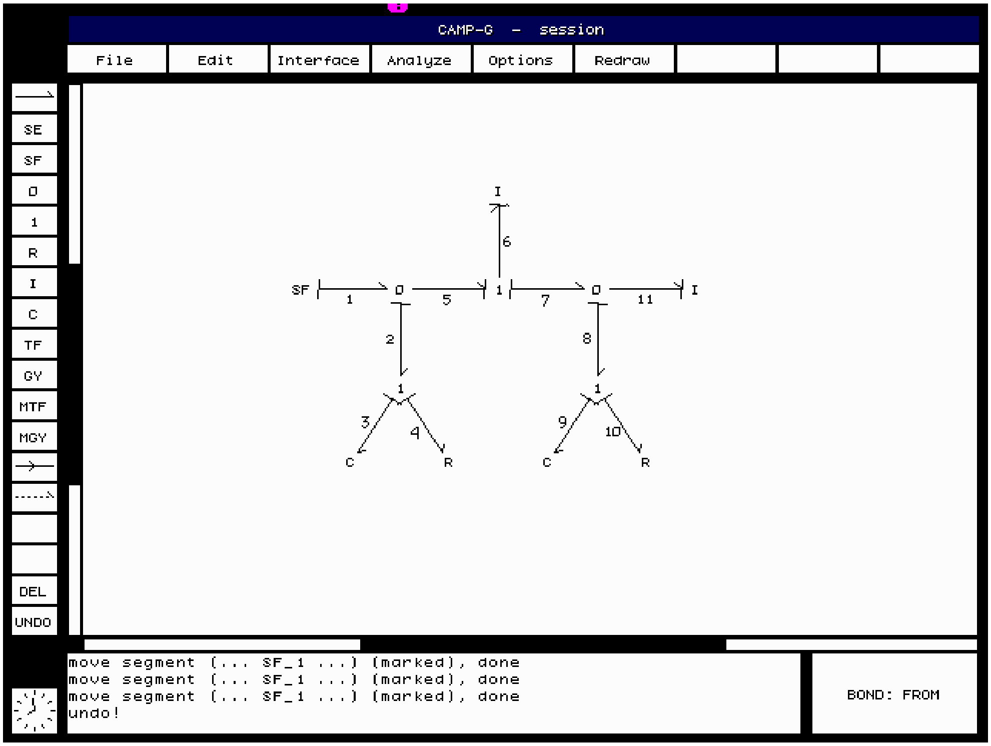


Fig. 4-12 Vehicle and seat belts Bond Graph Model

Bond Graph as Created in CAMPG



```
move segment (... SF_1 ...) (marked), done
move segment (... SF_1 ...) (marked), done
move segment (... SF_1 ...) (marked), done
undo!
```

BOND: FROM

Fig. 4-13 Bond Graph Model Generated in CAMPG

The SYSTEMATIC method was used to enter the bond graph model shown in *Fig. 4-13*, seen above. Below is a detailed description how this was done. The symbol (CUR) means to select with the cursor. The symbol <CR> means to enter from the keyboard.
****

CAMPG <CR> This brings up the CAMPG screen with a logo. Any movement of the mouse or typing any character, will clear the logo and show a blank screen or will bring up the latest model generated and stored in the SESSION.BG file.

EDIT	(CUR)	These next three steps clear the screen if there is an existing session file. If there is no previous SESSION.BG file, these steps are not necessary.
DELETE	(CUR)	
ALL	(CUR)	
YES	(CUR)	
OPTIONS	(CUR)	This pull-down menu selection will be used to turn on the STICKY function so that all the similar elements can be placed all at once. This step allows the SYSTEMATIC METHOD of building the bond graph model.
STICKY	(CUR)	
-ON-	(CUR)	
1	(CUR)	Select the (1) from the menu on the left to place the ONE JUNCTIONS.
	(CUR)	Move the cursor and click in the middle of the screen.
	(CUR)	Move the cursor 4 grids to the right and 4 grids down and click again to place the second (1).
	(CUR)	Move the cursor 8 grids to the left and click to put the third (1) on the screen.
0	(CUR)	Select the (0) from the left hand menu to place the ZERO JUNCTIONS on the screen.
	(CUR)	

	(CUR)	Click the cursor at 4 grids to the left of the (1) (middle of screen) and at 4 grids to the right of it.
C	(CUR)	Select C from the menu in order to place the capacitive elements (C) on the Bond graph.
	(CUR)	
	(CUR)	Place one of the (C) elements 2 grids below and 2 grids to the left of the (1) element on the left then move 8 grids to the right and place the other.
R	(CUR)	Select the resistive elements (R) from the left hand menu.
	(CUR)	
	(CUR)	Place these (R) elements 4 grids to the right of each (C) element.
I	(CUR)	Select the (I) element from the left menu.
	(CUR)	
	(CUR)	Place the two inertia elements (I) 4 grids above the central (1) and 4 grids to the right of the right most (0).
SF	(CUR)	Select the FLOW SOURCE from the menu on the left.
	(CUR)	Place this (SF) 4 grids to the left of the left most (0).
(bond symbol)	(CUR)	Select the BOND SYMBOL (top box in the left hand menu) to join all of the elements with bonds.
SF (screen)	(CUR)	Click on the (SF) on the screen.
0 (screen)	(CUR)	Click on the closest (0) on the screen.

0	(screen)	(CUR)	Click on the same (0).
1	(screen)	(CUR)	Click on the lower left (1) on the screen. There should be now have 2 bonds on the screen. Continue this process until the rest of the bonds have been created.

Notice that some of the bonds are red just after they are placed. This means that the system detects an error in the bond graph construction. These errors while the bond graph is being assembled are simply warnings to the user that the bond graph is not a close form system but rather some bonds are not complete yet. They also tell the user that the causality cannot be completed up to that point. If these errors continue after completion of the bond graph, it means that there are loops, derivative causality or incomplete bonds that will prevent the generation of a close form system of equations. The user needs to investigate and correct it.

The errors can be determined by inspection of the bond graph or with assistance from CAMPG. Click on ANALYZE, then EXPLAIN and then once again on the red bond or element. The DIALOGUE BOX will provide an explanation of the error. Most likely, the error will disappear after the bond graph has been completed. This feature is excellent to assist in defining correct bond graph models.

The user has now completed the bond graph model. You can look at the equations using ANALYZE and PEEK. This can be done by selecting PEEK under the ANALYZE button; the cursor will change to the "eye". Click the mouse on any element, junction or bond. The equations for that junction, bond or the constitutive relations of the physical elements will be displayed. Once the bond graph is completed, CAMPG is ready to process the model to generate an input file for ACSL.

This example showed how to use the STICKY feature and the SYSTEMATIC METHOD. The bond graph could also have been created by the SEQUENTIAL METHOD. This means connecting the elements immediately after they were placed on the screen instead of at the end. The elements and bond are laid out sequentially. Both of these methods create the same end product and the relative efficiency of each depends on the type of bond graph being constructed and the ability of the user to use the most familiar method for that person.

EXIT (CUR) This menu allows the user to select the simulation language, go back to DOS and saves the current model on the screen in a file named SESSION.BG.

TO ACSL (CUR) Select to generate a file with a model for ACSL.

4. CAMPG generates a computer model description and writes a file CAMPSL.CSL shown below. This file has been edited to include the values of the physical parameters initial conditions and external inputs. This input file follows the required ACSL syntax for simulation.

```
PROGRAM  CAMPACSL
"...... ACSL  INPUT FILE  ......"
                        "TITLE -  CRASH TEST MODEL   "
    INITIAL
    "...... INITIAL CONDITIONS ......"
            CONSTANT   Q3IN= 0.  , P6IN= 16763.96
            CONSTANT   Q9IN= 0.  , P11IN= 1117.6
        "..... TIME CONTROL (T=TIME)....."
                                        CINTERVAL  CINT= .005
            CONSTANT   FINTIM= 1.0
        "...... SYSTEM PHYSICAL PARAMETERS  ......"
            CONSTANT     C3 = .000003333        $ R4 = 80000.
            CONSTANT     I6 = 1500.                 $ C9 = .0001
            CONSTANT     R10 = 500.                 $ I11 = 100.
    END  $"OF INITIAL"
                        DYNAMIC
        DERIVATIVE
            ".... EXTERNAL INPUTS  SE=F(T),SF=F(T) ...."
                SF1 = 0.
```

```
                          "...... SYSTEM EQUATIONS  ......"
                                                           F1=SF1        $
F2=F1-F5
                               E1=E2          $   E5=E2
                               E2=E3+E4       $   F3=F2
                               F4=F2          $ DQ3=F3
                               E3=Q3/C3       $   E4=F4*R4
                               E6=E5-E7       $   F5=F6
                               F7=F6          $ DP6=E6
                               F6=P6/I6       $   F8=F7-F11
                               E7=E8          $   E11=E8
                               E8=E9+E10      $   F9=F8
                               F10=F8      $ DQ9=F9
                               E9=Q9/C9       $   E10=F10*R10
                               DP11=E11       $   F11=P11/I11
                          "...... STATE VARIABLES ......"
                            Q3= INTEG (DQ3,Q3IN )
                            P6= INTEG (DP6,P6IN )
                            Q9= INTEG (DQ9,Q9IN )
                            P11= INTEG (DP11,P11IN )
                          "TEMINATE CONDITIONS"
                            TERMT (T.GE.FINTIM)
                                      END  $"OF DERIVATIVE"
                                 END  $"OF DYNAMIC"
         END  $ "OF PROGRAM"
```

The causality and power flow can be verified since CAMPG will generate the bond graph causality and power flow tables shown below. These can stay in the file since they do not interfere with the ACSL input format and it will consider this tables as non-executable statements.

```
"********************   ********************"
   "....... BOND GRAPH ANALYSIS ......."

" POWER FLOW:"
" BOND    FROM                    TO"
" ----    ----                      --"
"   1   SF_1                   0_1_2_5"
"   2   0_1_2_5                  1_2_3_4"
"   3   1_2_3_4                  C_3"
"   4   1_2_3_4                  R_4"
"   5   0_1_2_5                         1_5_6_7"
"   6   1_5_6_7                         I_6"
"   7   1_5_6_7                         0_7_11_8"
"   8   0_7_11_8                        1_8_9_10"
"   9   1_8_9_10                        C_9"
"  10   1_8_9_10                        R_10"
"  11   0_7_11_8                        I_11"


" CAUSALITY FLOW:"

" NOTE:  FROM -----| TO"

" BOND    FROM                       TO"
" ----    ----                          --"
"   1   0_1_2_5                     SF_1"
"   2   1_2_3_4                         0_1_2_5"
"   3   C_3                             1_2_3_4"
"   4   R_4                             1_2_3_4"
"   5   0_1_2_5                         1_5_6_7"
"   6   1_5_6_7                         I_6"
"   7   0_7_11_8                        1_5_6_7"
"   8   1_8_9_10                        0_7_11_8"
"   9   C_9                             1_8_9_10"
"  10   R_10                        1_8_9_10"
"  11   0_7_11_8                        I_11"

END  $"OF PROGRAM"
```

5. Execute ACSL with the model shown in the previous section. This is done by issuing the commands:

   ACSLCLG CAMPSL   (PC)
   ACSL   CAMPSL

   The ACSL commands necessary for calculation of variables or plots are entered at this stage. The next step shows a summary of the commands used in this simulation.

6. The simulation was speed up using the SETUP file shown below. The "Setup" file was used to generate sets of graphical output with options and commands stored in sections with labels A, B, C, E, F. Several cases were simulated at different speeds and with different parameter values.

```
SET TITLE = "SEAT BELT TEST "
PREPAR T,E3,E4,E6,F6,Q3,E9,E10,E11,F11,Q9
OUTPUT T,E3,E4,E6,F6,Q3,E9,E10,E11,F11,Q9,'NCIOUT'=10
SET TCWPRN = 72
START

PROCED A
    SET TITLE = "SPRING FORCE (E3), DAMPER FORCE (E4)"
    SET CALPLT=.TRUE.,STRPLT=.F.,GRDSPL=.F.
    PLOT "XHI"=FINTIM, "XTAG"="(SEC)", E3, E4
END

PROCED B
    SET TITLE = "FORCE ACTING ON THE CAR (E6) AND"
                "DISPLACEMENT(Q3)"
    SET CALPLT=.TRUE.,STRPLT=.T.,GRDSPL=.T.
    PLOT "XHI"=FINTIM, "XTAG"="(SEC)", E6 ,Q3
END

PROCED C
    SET TITLE ="SPRING FORCE(E9) AND DAMPER FORCE(E10)"
    SET CALPLT=.TRUE.,STRPLT=.F.,GRDSPL=.F.
    PLOT "XHI"=FINTIM,"XTAG"="(SEC)", E9,E10
END

PROCED E
     SET TITLE = "FORCE ACTING ON THE PASSENGER (E11)"
                "DISPLACEMENT(Q9) AT SPEED 25 MILE/H"
    SET CALPLT=.TRUE.,STRPLT=.F.,GRDSPL=.F.
    PLOT "XHI"=FINTIM, "XTAG"="(SEC)", E11 ,Q9
END

PROCED F
    SET TITLE = "FORCE ACTING ON THE PASSENGER (E11)"
                "DISPLACEMENT(Q9) AT SPEED 25 MILE/H"
```

```
          SET CALPLT=.F.,STRPLT=.T.,YASSPL=1.0,GRDSPL=.T.
          PLOT "XHI"=FINTIM, "XTAG"="(SEC)",E11,Q9
     END
     SET PRNPLT=.FALSE.,PLT=6
     SET CMD=5
```

DESIGN CRITERIA

The simulation must produce a design of the seat belts and the bumper so that it satisfies the following conditions:

1 He doesn't hit the windshield if he travels at 25 and at 55 mph.

2. What is the force acting on his chest and waist at 25 mph and at 55 mph. Compare the data on injuries and determine if chest or internal injury occurs if: (1) he wears a seat belt only; (2) he wears a seat belt and a shoulder strap.

3. What is the "critical" maximum velocity (when he is safe) at which impact occurs ?. Hitting the windshield, chest injury, internal injury, seat belt failure, strap failure should not occur.

4. If he travels without a seat belt. How long does it take for him to hit the windshield at 25 mph, 40 mph, 55 mph. What is the force acting on him on impact at 25 mph, 40 mph, 55 mph.

RESULTS

The results obtained from the simulation can be obtained in the form of numerical values or in the form of plots of variables as a function of time. Several designs with different kinds of bumpers and shock absorbers were tried. One of those is shown in *Fig. 4-14 and Fig 4-15*. These simulations allow the user to make an optimum decision to satisfy the design requirements. The user is able at this point to decide which is the best design and why. He can perform, as many simulations as he thinks are necessary. In this case it was found from *Fig.4-14 and Fig. 4-15* that at

25 mph the dummy did not hit his head on the windshield. Its maximum displacement was 0.81m. Less than the 1.00 m allowed. The force acting on his body was 9,310 newtons. However this is enough to produce chest injury. The maximum limit allowed is 6,688 newtons. No failure of the seat belts occurs since they can resist a load of 13,340 newtons.

The table shown below illustrates the results of the different simulations considering different velocities and physical parameters.

INITIAL	**N OF**	**BUMPER**		**SEAT BELTS**		**DUMMY**	
VELOCITY	**BELTS**	**K2**	**B2**	**K1**	**B1**	**E11**	**Q9**
		[N/m]	**[N-s/m]**	**[N/m]**	**[N-s/m]**	**[N]**	**[m]**
25	**1**	**300,000**	**80,000**	**10,000**	**500**	**9,310**	**0.8167**
25	**2**	**300,000**	**80,000**	**20,000**	**1,000**	**13,147**	**0.5144**
55	**1**	**300,000**	**80,000**	**10,000**	**500**	**20,483**	**1.7968**
55	**2**	**300,000**	**80,000**	**20,000**	**1,000**	**29,035**	**1.1300**
55	**1**	**300,000**	**80,000**	**10,000**	**1,000**	**25,547**	**1.3780**
55	**1**	**300,000**	**80,000**	**10,000**	**1,500**	**26,714**	**1.1100**
55	**1**	**300,000**	**80,000**	**8,000**	**1,500**	**25,990**	**1.1670**
55	**1**	**300,000**	**80,000**	**5,000**	**3,000**	**36,639**	**0.7500**
55	**2**	**300,000**	**50,000**	**5,000**	**3,000**	**31,184**	**0.7810**
55	**2**	**300,000**	**10,000**	**5,000**	**3,000**	**25,426**	**1.0360**
55	**2**	**100,000**	**10,000**	**5,000**	**3,000**	**15,986**	**0.8580**
55	**2**	**50,000**	**10,000**	**5,000**	**3,000**	**13,129**	**0.7440**

Table 7

The impact at 55 mph is shown in *Fig. 4-15 and Fig. 4-17*. The displacement of the dummy is 1.79m so he hits the windshield in 0.065 sec. Chest injury also occurs at 20,483 newtons. The values of the shock absorbers can be changed in the bumper and in the seat belts. Fig.23 shows what happens if he doesn't use a seat belt. The dummy hits the windshield in about .1 sec at 25 mph but in just 0.05 sec at 55 mph without a seat belt.

This example illustrates the whole process of modeling and simulation using CAMPG/ACSL for linear systems. The next section will explore other capabilities with non-linear systems.

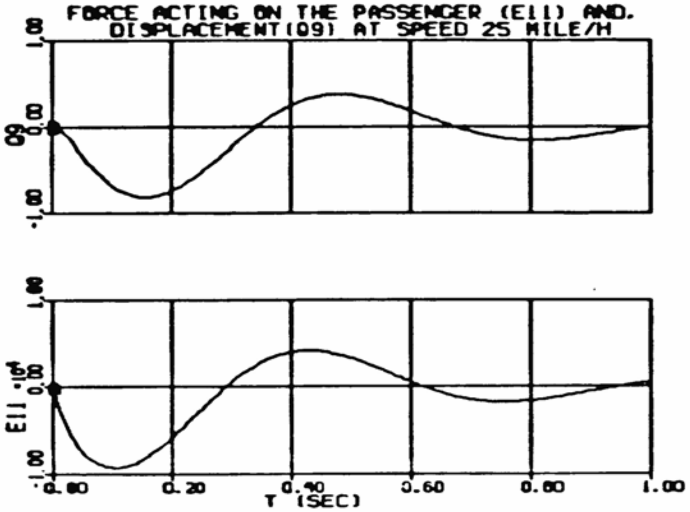


Fig. 4-14 Force, Displacement at 25 MPH

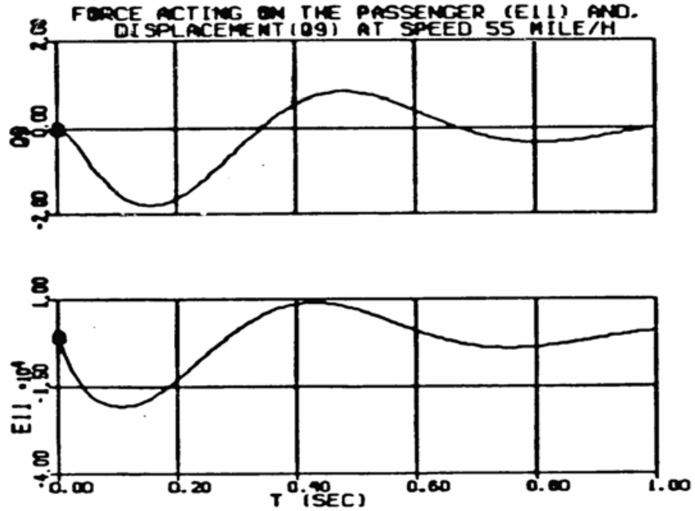


Fig. 4-15 Force, Displacement at 55 MPH

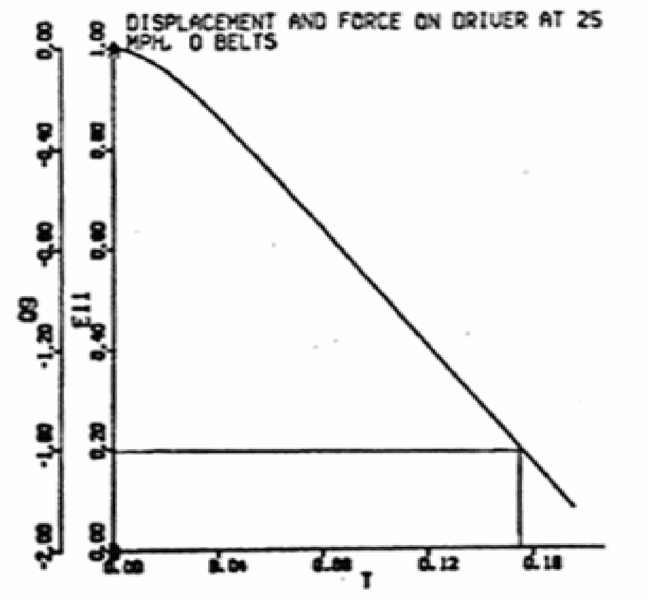


Fig 4-16 Crash Test Simulation with no seat belts at 25 MPH

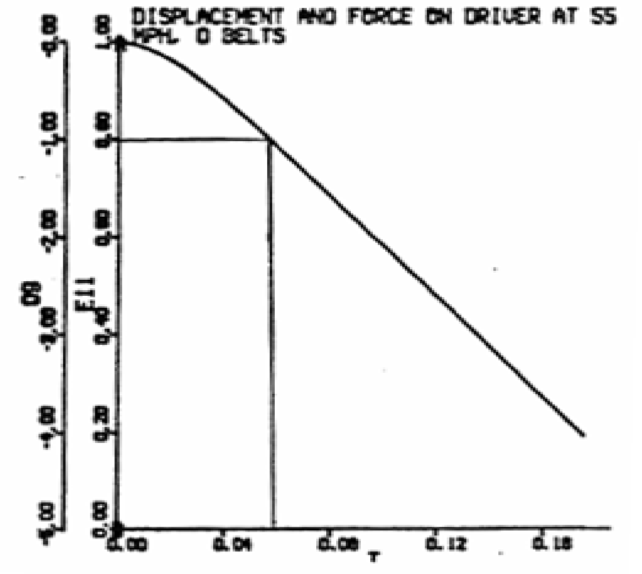
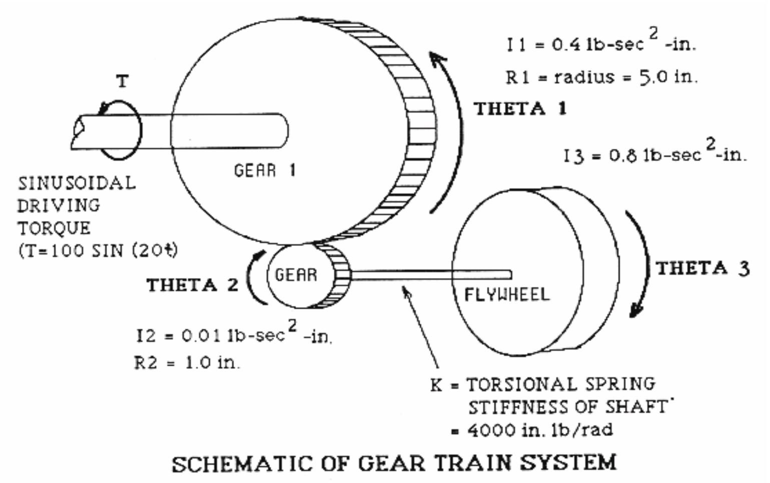


Fig 4-17 Crash Test Simulation with no seat belts at 55 MPH

4.10 Nonlinear System Example - Gear Train with Backlash

PROBLEM:
Design of precision gear trains requires analysis of forces, velocities, torques and realistic models considering the tolerances and slack between gear teeth. This analysis is important in order to prevent fatigue failure on gear teeth and the transmitting shafts. This will contribute to determine the materials, size of parts and tolerance adjustments that are related to the generation of contact forces. This involves making a dynamic model and performing the analysis of the gear train considering the backlash between the gear teeth.

The system shown in *Fig. 4-18*, seen below, consists of a gear set and a flywheel. Gear 1 is driven by a cyclic torque described by a harmonic function. The system drives the flywheel through a set of gears having excessive backlash. The shaft connecting gear 2 and the flywheel is not rigid, it has a torsional spring constant of K= 4000 in-lb/radian.



T
I1 = 0.4 lb-sec^2 -in.
R1 = radius = 5.0 in.
THETA 1
I3 = 0.8 lb-sec^2-in.
GEAR 1
SINUSOIDAL DRIVING TORQUE (T=100 SIN (20t)
THETA 2
GEAR
FLYWHEEL
THETA 3
I2 = 0.01 lb-sec^2 -in.
R2 = 1.0 in.
K = TORSIONAL SPRING STIFFNESS OF SHAFT = 4000 in. lb/rad
SCHEMATIC OF GEAR TRAIN SYSTEM

Fig 4-18 Physical System Model of Drive Train

The contact force between the gear teeth is defined by a dead space non-linear function. The force increases linearly when the gears are in contact but is zero when they are not. Since the input torque is a harmonic function, the teeth are not always in contact and therefore a nonlinear model exists. The diagram of this function is shown in *Fig. 4-19*, seen below. The position of the gears, forces and velocities are of interest in the design of the gear train.

Nonlinear Dead Space Contact

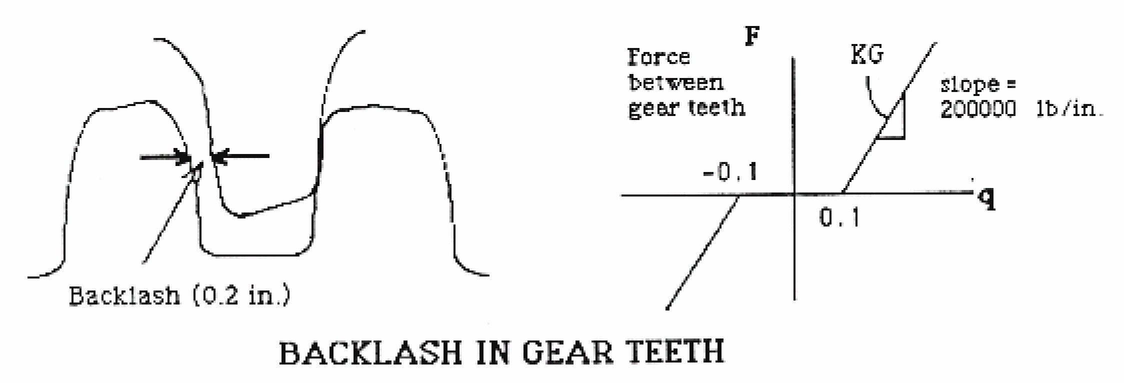


Fig. 4-19 Mathematical functions of backlash

OBJECTIVES:

1. Generate an engineering model of the gear train shown in *Fig. 4-18*
2. Transform the engineering model of the real system into a computer model for simulation using the Computer Aided Modeling Program (CAMPG).
3. Using computer simulation in an interactive way generate numerical and graphical output using the Advanced Continuous Simulation Language (ACSL).
4. Interpret the results and make design decisions.

PROCEDURE FOR SOLUTION

1. GENERATE AN ENGINEERING MODEL.- The system shown in *Fig. 4-18* is the engineering model of the real system. The stiffness elements are the shafts; the inertia element is the flywheel and the gears.

2. GENERATE THE CORRESPONDING BOND GRAPH –
 Make a Bond Graph model of the gear train. Consider the inertia of the gears and the flywheel, the compliance effect of the drive shaft and the slack between the gear teeth. *Fig. 4-20* shows this model. The backlash is modeled as a nonlinear compliant element (C) because the constitutive relation between contact force and the relative displacement is defined in *Fig. ure 132*. The force function is directly related to the relative displacement between the teeth. This relative displacement at the gear teeth point of contact is calculated by the integration of the relative velocity between the two gears. The relative tangential velocity is obtained by multiplying the angular velocity of the gear by their respective radius and finding the difference in tangential velocities a the point where the gears are in contact. This is accomplished by the TF elements that make this transformation between the angular velocity and the tangential velocity. The C element performs the integration and controls also the force using the defined DEAD SPACE function that represents the time the gears are in contact as well as when they are not.

3. CAMPG - Generate a description of the graph using the graphics capabilities of the Computer Aided Modeling Program with Graphical input (CAMPG). This model is shown in *Fig. 4-21* and is seen below.
 In the previous section the linear model was constructed using the SYSTEMATIC method. In the case of the gear teeth, the SEQUENTIAL method is used to generate the bond graph and demonstrate how to construct bond graph models using this method and CAMPG. Just as a brief reminder, the SEQUENTIAL method consists of assembling of all bonds immediately following the placement of the elements and 0 or 1 junction. This method helps to illustrate other editing features of CAMPG such as the moving of whole bond graphs or parts of them to other parts of the screen.

Bond Graph Model

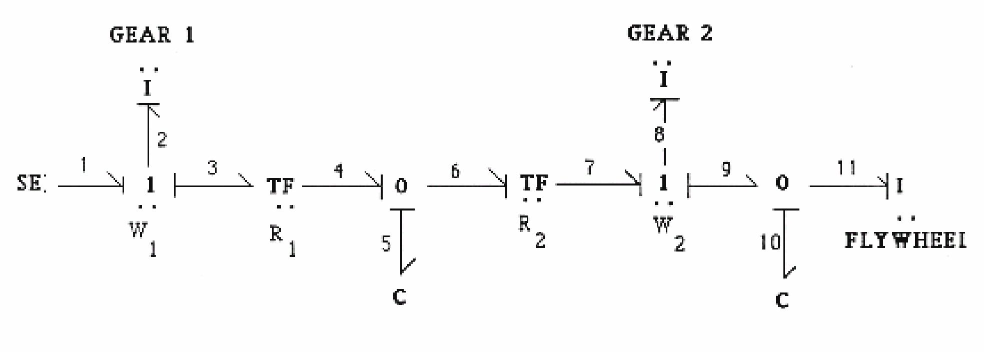
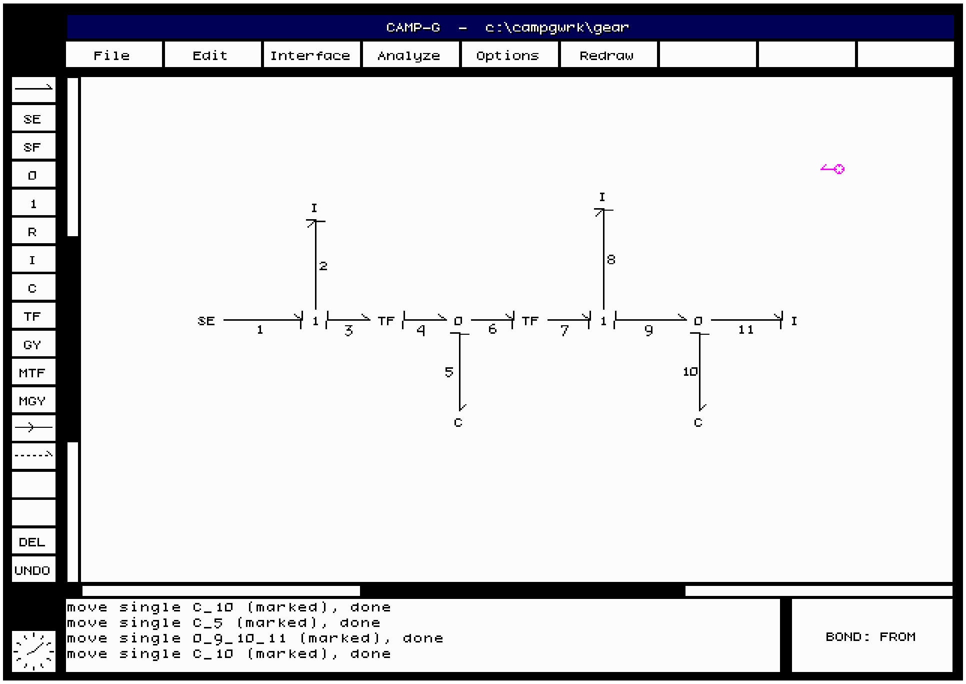


Fig 4-20 Gear Train Bond Graph Model

Bond Graph Model in CAMPG



```
move single C_10 (marked), done
move single C_5 (marked), done
move single 0_9_10_11 (marked), done
move single C_10 (marked), done
```

BOND: FROM

Fig 4-21 Gear Train Model in CAMPG

The bond graph of *Fig. 4-21* was constructed using the following steps:

CAMPG <CR> Start CAMPG and brings up the logo containing the user name and the license number. Please refer to this number for maintenance and updates.

(space bar) <CR> This clears the screen preparing it for a drawing. Any other character or movement of the mouse will do the same.

EDIT (CUR) The next three steps clear the session file. If you have no previous SESSION.BG file. These steps are not necessary.
DELETE (CUR)
ALL (CUR)
YES (CUR)

SE (CUR) There is a box on the left icon menu which has the SE symbol in it. This is the SOURCE EFFORT element in the bond graph. Pick the SE with the mouse.

(Left of screen) (CUR) Place the (SE) on the screen by moving the cursor to the middle of the vertical left edge of the drawing screen and a couple of grids to the right and clicking the left button of the mouse. The model can start in any location of the screen.

1 (CUR) Pick the 1 junction from the menu on the left and place it two grids to the right of the SE element. Both elements are red now.

(CUR) You will see on the Status Box the message "Bond: from" and the cursor turned to a small circle and an arrow pointing left. Click on the SE element. The cursor will change direction as a circle and an arrow pointing right. The Status Box reads "Bond: to". Click the cursor on the 1 junction or as close to it as you can. The bond that joins the SE element and the 1 junction will be displayed along with a bond number and the causality assignment.

Note that the 1 is red, this indicates the bond graph is not complete. Any bond or element in red indicates some difficulty with the graph. The user can get an explanation in any case. To do this click the mouse on the ANALYZE button, choose explain (the cursor will change) and then click on 1 element. The message displayed on the dialogue box is "explain 1_1: too few bonds".

I (CUR) Now select an (I) element by clicking the mouse while the cursor is on the I button on the elements menu. Place these two grids above the 1 junction by moving the cursor and clicking the mouse. The distance is arbitrary.

(CUR) Draw the bond between the 1 and the I element; click the mouse on the 1 and then on the I. The cursor will change direction on each click and the bond 2 will appear on the screen.

TF (CUR) Select the TF element from the menu and place it to the right of the 1 junction.

(CUR) Status Box reads "Bond: from" and the cursor turned to a small circle and an arrow pointing left.

Click on the 1 junction. The cursor again changes direction as a circle and an arrow pointing right. The Status Box reads "Bond: to". Click the cursor on the 1 junction or as close to it. The bond that joins the junction and the element will be displayed with its corresponding bond number one higher than the previous one and causality assignment.

0 (CUR) Pick a 0 junction, place it to the right of the TF.

TF(screen) (CUR)
0 (screen) (CUR) This should create a bond from the (TF) element to the (0) junction.

C (CUR) Select an (C) and place it below the (0).
(CUR)

0 (screen) (CUR) Click on the (0) element on the screen.
C (screen) (CUR) Click on the (C) element on the screen. A bond should appear between these two elements.

TF (CUR) Select (TF) and place it to the right of the 0 junction.

0 (screen) (CUR)
TF(screen) (CUR) This should create a bond from the (0) junction and the (TF) element. The number of the bond will appear in the middle of the bond as it has for all the other bonds.

1 (CUR) Pick a 1 junction from the menu and place it to the right of the TF6x7.

TF(screen) (CUR) Click the mouse on the TF for FROM status.

1 (screen) (CUR) Click on the 1 junction. Note again that the numbers of the bonds appear automatically in the middle of the bonds. In this case (7).

I (CUR) Click on the I icon in the menu. Place the I above the last 1 junction.

1 (screen) (CUR)
I (screen) (CUR) Generates a bond between the (1) and the (I) element.

0 (CUR) Pick the (0) from the menu, place it the right of the last (1) junction.

1 (screen) (CUR)
0 (screen) (CUR) Draws a bond between 1 and the 0 junction.

C (CUR) Pick (C) from the menu and place it below the last (0) junction.

0 (screen) (CUR)
C (screen) (CUR) Generates bond between (0) and (C).

I (CUR) Pick (I) and place it to the right of the (0) junction.

0 (screen) (CUR)
I (screen) (CUR) This step completes the bond graph by drawing a bond from the last (0) junction to the (I) element. Now the whole bond graph can be moved to the right to have it on the center of the screen. This is done with the following steps.

EDIT (CUR) Pick the EDIT button and select the MOVE button. There will be two choices. SINGLE and SEGMENT. Pick SEGMENT.

SEGMENT(CUR) The cursor will change shape to a cross. Click the mouse on the SE element (it can be any other element or junction). The bond graph segment will turn blue.

(CUR) Move the cursor to the desired new location for the element picked. The bond graph will be redrawn in the new location.

All junction and elements have their corresponding bonds, numbers, and causality marks. If there is any one bond or element on the screen that it is red, use the ANALYZE button and pick EXPLAIN, then click on the red bond or element. A message on the dialogue box will indicate the status or error message.

3. GENERATE AN ACSL INPUT FILE. - Continuing from the previous step, once the bond graph has been completed pick the EXIT button and within it the ACSL option. CAMPG will generate the CAMPSL.CSL file used as ACSL input. The model description here will help illustrate some features of this file not yet discussed. CAMPG will generate a set of instructions at the beginning of the file as shown below. These are helpful instructions to structure the input file correctly. It also includes an explanation of the variable equivalences in different energy domains. This gives the physical interpretation to the variables in the equations and expressions.

4. ENTER PARAMETER VALUES. - Edit the CAMPG model to enter the linear and non-linear constitutive relations of physical elements into the ACSL input file. The completed model input file was shown in the previous section. Note the non-linear constitutive relation of the C5 element is entered as a modification of the linear version of E5= 1/C5. Q5. Here the non linear equation is E5= KG*DEAD(-0.1,0.1,Q5).

This model description in the form of source code is shown is shown below.

```
            " THIS  IS A - CAMP - GENERATED MODEL DESCRIPTION: "

            "  1.- EDIT THIS FILE. ENTER VALUES OF PHYSICAL PARAMETERS, "
            "      INITIAL CONDITIONS, INPUTS AND TIME CONTROLS IN "
            "      PLACES WHERE THE QUESTION MARKS APPEAR. "

            "  2.- FOR NON-LINEAR SYSTEMS. REPLACE THE LINEAR "
            "      RELATIONS BY NON-LINEAR FUNCTIONS. "
            "      FOLLOWING THE PROPER CAUSAL RELATIONS. "

            "  3.- THE TABLE BELOW PROVIDES A GUIDELINE FOR "
            "      PHYSICAL MEANING OF GENERALIZED VARIABLES "
            "      USED IN BOND GRAPH NOTATION. "


        PROGRAM  CAMPACSL   $ "...... ACSL  INPUT FILE  ......"
"Gear train with backlash Non-linear model"
            INITIAL          $ "...... INITIAL CONDITIONS ......"
                CONSTANT   P11IN= 0. , P2IN= 0., P8IN= 0., Q5IN= 0.
                CONSTANT   Q10IN= 0.
            "..... TIME CONTROL (T=TIME)....."
                CINTERVAL  CINT= 0.0008
                CONSTANT   FINTIM= 1.0
            "...... SYSTEM PHYSICAL PARAMETERS  ......"
                CONSTANT I2 = 0.4 , T3x4 = 5.,  ...
            T6x7 = 1.0 , I8 = 0.01, ...
                I11 = 0.8,  KG= 200000.
                C10 = 1./4000.
                PII= 4*ATAN(1.)     $ "DEFINE PI"
                RADEG=360./(2.*PII)
            END  $"OF INITIAL"
            DYNAMIC
                DERIVATIVE
                ".... EXTERNAL INPUTS  SE=F(T),SF=F(T) ...."
                    SE1 = 100.*Sin(20.*T)
                "...... SYSTEM EQUATIONS  ......"
                    e1=SE1                  $   f1=f2
                    e2=e1-e3                $   f2=P2/I2
                    e3=e4*T3x4              $   f3=f2
                    e4=e5               $   f4=f3*T3x4
                    e5=KG*DEAD(-0.1,0.1,Q5)      $   f5=f4-f6
                    e6=e5               $   f6=f7/T6x7
```

```
              e7=e6/T6x7              $   f7=f8
              e8=e7-e9                $   f8=P8/I8
              e9=e10                  $   f9=f8
              e10=Q10/C10             $   f10=f9-f11
              e11=e10                 $   f11=P11/I11
              dP11=e11                $   dP2=e2
              dP8=e8                  $   dQ5=f5
              dQ10=f10                $
         "...... STATE VARIABLES ......"   $ " Calculate Angles "
              P11= INTEG (dP11,P11IN )     $  Q2= INTEG(F2,0.0)
              P2= INTEG (dP2,P2IN )        $  Q8= INTEG(F8,0.0)
              P8= INTEG (dP8,P8IN )        $  Q11=INTEG(F11,0.0)
              Q5= INTEG (dQ5,Q5IN )
              Q10= INTEG (dQ10,Q10IN )
         "TEMINATE CONDITIONS"
              TERMT (T.GE.FINTIM)
         "      CHANGE VARIABLE NAMES"
              F=E5                 $  " FORCE BETWEEN TEETH"
              W1= F2               $  " ANGULAR VELOCITY OF GEAR 1"
              W2= F8               $  " ANGULAR VELOCITY OF GEAR 2"
              W3=F11               $  " ANGULAR VELOCITY OF FLYWHEEL"
              THETA1= Q2*RADEG $"ANGLE OF ROTATION OF GEAR 1"
              THETA2= Q8*RADEG $"ANGLE OF ROTATION OF GEAR 2"
              THETA3= Q11*RADEG$"ANGLEOF ROTATION OF FLYWHEEL"
              TWIST = Q10*RADEG  $" SHAFT ANGLE OF TWIST"
              WD1= DP2/I2             $"ANGULAR ACCELERATION OF GEAR 1"
              WD2= DP8/I8             $"ANGULAR ACCELERATION OF GEAR 2"
              WD3= DP11/I11  $"ANGULAR ACCELERAITON OF FLYWHEEL"
                             END  $"OF DERIVATIVE"
    END  $"OF DYNAMIC"
    TERMINAL
    END  $"OF TERMINAL"


    "********************     *******************"
       "...........BOND GRAPH NOTATION............."
      "PHYSICAL MEANING OF GENERALIZED VARIABLES USED:"
"-------------------------------------------------------------------------------------------"
"                    MECHANICAL                 ELECTRICAL    HYDRAULIC   "
"                 | TRANSLATION |ROTATION|
"
"-------------- |---------------------|---------------|------------------|--------------------  "
"e (effort)      |force                    |torque        |voltage          |pressure             "
```

```
"f (flow)       |velocity              |ang vel.      |Current               |volume flow rate "
"q (gen disp)  |displacement        |angle          |charge           |volume                  "
"p (gen mom)|momentum            |ang.Moment  |Flux linkage       |pressure moment "
"------------------------------------------------------------------------------------"
" TF (m) (transformer modulus)      SE source effort                                   "
" GY (r) (gyrator modulus)          SF source flow                                     "
"--------------------------------------------------------------------------------------------    "
              "********************    *******************"
                    "....... BOND GRAPH ANALYSIS ......."

 "SYSTEM  DESCRIPTION:"

" POWER FLOW:"
" BOND    FROM                        TO"
" ----    ----                        --"
"   1   SE_1                          1_1_2_3"
"   2   1_1_2_3                           I_2"
"   3   1_1_2_3                           TF_3_4"
"   4   TF_3_4                            0_4_5_6"
"   5   0_4_5_6                           C_5"
"   6   0_4_5_6                           TF_6_7"
"   7   TF_6_7                            1_7_8_9"
"   8   1_7_8_9                           I_8"
"   9   1_7_8_9                           0_9_10_11"
"  10   0_9_10_11                     C_10"
"  11   0_9_10_11                     I_11"

" CAUSALITY FLOW:"

" NOTE:  FROM -----| TO"

" BOND    FROM                        TO"
" ----    ----                        --"
"   1   SE_1                          1_1_2_3"
"   2   1_1_2_3                           I_2"
"   3   TF_3_4                            1_1_2_3"
"   4   0_4_5_6                           TF_3_4"
"   5   C_5                           0_4_5_6"
"   6   0_4_5_6                           TF_6_7"
"   7   TF_6_7                            1_7_8_9"
"   8   1_7_8_9                           I_8"
"   9   0_9_10_11                     1_7_8_9"
"  10   C_10                              0_9_10_11"
```

```
 "  11   0_9_10_11                        I_11"
END  $"OF PROGRAM"
```

The model causality and power flow tables are generated in the ACSL input file in order to assist the user to verify the input model structure and power flow.

The instructions at the beginning as well as the explanation of the variables in different energy domains or the verification of causality and power flow can be included in the ACSL input file as CAMPG generates this in the form so that ACSL considers that as no executable statements. The user can erase on or both of these information sections.

5. RUN ACSL .- Using the CAMP-ACSL model, perform a computer simulation to obtain the values of variables that will help make design decisions. These include the torques, forces and displacements of the gears, the flywheel and the shaft. These variables are:

F	Force between teeth"
Q5	Relative displacement between teeth
W1	Angular velocity of gear 1"
W2	Angular velocity of gear 2"
W3	Angular velocity of flywheel"
Theta1	Angle of rotation of gear 1"
Theta2	Angle of rotation of gear 2"
Theta3	Angle of rotation of flywheel"
Twist	Shaft angle of twist"
Wd1	Angular acceleration of gear 1"
Wd2	Angular acceleration of gear 2"
Wd3	Angular acceleration of flywheel"
SE1	Input torque
E2	Torque on gear 1
E10	Torque on shaft

The interactive commands used in ACSL are shown below along with some of the calculations in the form of numerical tables.   The PREPAR command is used to prepare the variables for calculation and graphical output. The OUTPUT command is used to display the calculations on the screen. This can be turned off by the command OUTPUT 'CLEAR'. This allows the user to prepare different variables for calculation and then plotting. The RANGE command helps to find the maximum and minimum values of the design variables. The plots are generated using the options explained in Section 5.2.2. The variable 'NCIOUT' defines the number of calculation that the computer will go through before it prints a value. The following output shows the variable values every 100 steps.

```
ACSL> SET TITLE="GEAR TRAIN WITH BACKLASH"
ACSL> PREPAR T, F,Q5,W1,W2,W3,THETA1,THETA2,THETA3,TWIST,...
          WD1,WD2,WD3,SE1,E2,E10
ACSL>
ACSL> START
         RANGE 'ALL'
               T 0.        1.00000000
               F-799.510000            876.132000
               Q5-0.10399800           0.10438100
               W1-3.05866000           3.62343000
               W2-20.7567000           21.5832000
               W3-0.20755400           2.64094000
               THETA1 0.                    14.3570000
               THETA2-0.24510000       66.8484000
               THETA3 0.                    66.1257000
          TWIST-2.08848000         2.03426000
               WD1-10772.2000          9755.07000
               WD2-73588.0000          85657.6000
               WD3-182.254000          77.523000
               SE1-99.9999000          99.9998000
               E2-4308.87000           3902.03000
               E10-145.803000          142.018000
```

```
ACSL>     OUTPUT T,
           F,Q5,W1,W2,W3,THETA1,THETA2,THETA3,TWIST,...
          WD1,WD2,WD3,SE1,E2,E10,"NCIOUT"=100

ACSL>  SET TCWPRN=72       $" FORCE 3 COLUMN OUTPUT WIDTH
ACSL> START

          T 0.                    F 0.                        Q5 0.
          W1 0.                   W2 0.                   W3 0.
          THETA1 0.                   THETA2 0.               THETA3 0.
          TWIST 0.                    WD1 0.                  WD2 0.
          WD3 0.                  SE1 0.                  E2 0.
          E10 0.

          T 0.08000000            F 0.                        Q5 0.08635910
         W1 0.02511270            W2-10.9065000           W3 1.42032000
         THETA1 1.42483000  THETA2 2.17613000 THETA3 1.98043000
         TWIST 0.19569700   WD1 249.893000      WD2-1366.22000
         WD3 17.0778000     SE1 99.9574000      E2 99.9574000
         E10 13.6622000

         T 0.16000000             F 0.                        Q5 0.07939610
         W1-0.74132100            W2-1.68343000           W3 2.59304000
         THETA1 3.03126000  THETA2 10.6072000 THETA3 11.2325000
         TWIST-0.62526200   WD1-14.5935000     WD2 4365.15000
         WD3-54.5644000     SE1-5.83741000     E2-5.83741000
         E10-43.6515000

         T 0.24000000             F 0.                        Q5-0.05020320
         W1 2.02947000            W2 3.56703000           W3 0.89309100
         THETA1 3.50849000  THETA2 20.4189000 THETA3 20.1499000
         TWIST 0.26899500   WD1-249.041000     WD2-1877.94000
         WD3 23.4742000     SE1-99.6165000     E2-99.6165000
         E10 18.7794000

         T 0.32000000             F 0.                        Q5-0.04890670
         W1-0.09512880            W2-12.9536000           W3 0.17995200
         THETA1 3.70499000  THETA2 21.3271000 THETA3 21.8639000
         TWIST-0.53677700   WD1 29.1373000     WD2 3747.41000
         WD3-46.8426000     SE1 11.6549000     E2 11.6549000
         E10-37.4741000

         T 0.40000000             F 0.                        Q5 0.07155820
         W1-1.10078000            W2 12.7074000           W3 1.38311000
         THETA1 6.00811000  THETA2 25.9406000 THETA3 24.1799000
         TWIST 1.76062000   WD1 247.340000      WD2-12291.4000
         WD3 153.643000     SE1 98.9358000      E2 98.9358000
```

```
E10 122.914000

T 0.48000000             F 0.                          Q5-0.02229690
W1 0.63115600            W2 14.8046000          W3 2.23269000
THETA1 6.67062000  THETA2 34.6306000 THETA3 33.9018000
TWIST 0.72881400      WD1-43.5816000       WD2-5088.08000
WD3 63.6010000         SE1-17.4327000        E2-17.4327000
E10 50.8808000

T 0.56000000             F 0.                          Q5-0.06954550
W1-1.85102000            W2-7.48477000          W3 1.27490000
THETA1 7.80752000  THETA2 43.0223000 THETA3 42.2949000
TWIST 0.72735000      WD1-244.794000       WD2-5077.86000
WD3 63.4732000         SE1-97.9178000        E2-97.9178000
E10 50.7786000

 T 0.64000000            F 0.                          Q5 0.00757349
W1-1.29959000            W2-4.93688000          W3 0.22562900
THETA1 8.84244000  THETA2 43.7783000 THETA3 43.5761000
TWIST 0.20214300      WD1 57.8774000        WD2-1411.22000
WD3 17.6403000         SE1 23.1510000         E2 23.1510000
E10 14.1122000

T 0.72000000             F 0.                          Q5 0.06375560
W1-2.36478000            W2 5.46525000          W3 1.74294000
THETA1 9.99345000  THETA2 46.3143000 THETA3 46.5299000
TWIST-0.21561100      WD1 241.414000       WD2 1505.25000
WD3-18.8156000         SE1 96.5658000        E2 96.5658000
E10-15.0525000

T 0.80000000             F 0.                          Q5-0.04296190
W1-0.01586070            W2 13.1844000          W3 2.28386000
THETA1 10.7690000  THETA2 56.3064000 THETA3 56.5460000
TWIST-0.23965500      WD1-71.9759000       WD2 1673.11000
WD3-20.9138000         SE1-28.7904000       E2-28.7904000
E10-16.7311000

T 0.88000000             F 0.                          Q5-0.07345380
W1-1.52376000            W2 5.60466000          W3 0.93763800
THETA1 12.0746000  THETA2 64.5815000 THETA3 64.4084000
TWIST 0.17305700      WD1-237.211000       WD2-1208.17000
WD3 15.1021000         SE1-94.8845000        E2-94.8845000
E10 12.0817000
```

```
T 0.96000000            F 0.                     Q5 0.08378780
W1-1.28332000           W2 5.18064000          W3 0.13954800
THETA1 14.0324000  THETA2 65.3612000 THETA3 65.3053000
TWIST 0.05589940     WD1 85.8286000        WD2-390.252000
WD3 4.87814000       SE1 34.3315000         E2 34.3315000
E10 3.90252000

T 1.00000000            F 0.                     Q5 0.05285740
W1 0.48549300           W2 4.70774000          W3 0.63250100
THETA1 13.9239000  THETA2 66.5909000 THETA3 66.1257000
TWIST 0.46518100     WD1 228.236000        WD2-3247.57000
WD3 40.5947000       SE1 91.2945000         E2 91.2945000
E10 32.4757000

ACSL>  STOP
```

6. USE OF SETUP FILES IN SIMULATION. - Using ACSL interactively is very useful and the designer gains an insight of the system and its performance as well as modeling errors. The numerical and graphical results can be obtained very quickly and without much typing of commands and specification for plots if a set of this specification is stored in a SETUP file. The SETUP file shown below was used to study the dynamic performance of the gear train. Using a SETUP file the simulation can be quick and the plots can be generated immediately on the screen or to the hard copy device available on the user's computer. This is helpful for running multiple simulations as well as multiple plots. The following file contains each plot specification defined by the PROCED and the END keywords. If using the PC, the CMD (Command control) is delegated to the SETUP file by the command ACSL> SET CMD=10. Unit 10 is the default unit associated with the SETUP file 'GEAR.CMD'. The default option is that the SETUP file has the same name as the model file and the CMD file type.

```
SET TITLE="GEAR TRAIN WITH BACKLASH "
PREPAR      T, F,Q5,W1,W2,W3,THETA1,THETA2,THETA3,TWIST,...
            WD1,WD2,WD3,SE1,E2,E10
```

```
OUTPUT      T, F,Q5,W1,W2,W3,THETA1,THETA2,THETA3,TWIST,...
            WD1,WD2,WD3,SE1,E2,E10,"NCIOUT"=100
SET TCWPRN=72       $" FORCE 3 COLUMN OUTPUT WIDTH "
PROCED AA
  SET TITLE="ANGULAR ACCELERATION, GEARS AND FLYWHEEL"
   SETPRNPLT=.F.,CALPLT=.F.,STRPLT=.T.,GRDSPL=.T.,YINSPL=1.0,YASSP
                  L=.5
  PLOT"XAXIS"=T,"XTAG"="(SEC)",WD1,WD2,WD3,"TAG"="RAD/SxS"
END
PROCED BB
  SET TITLE="   ANGULAR VELOCITY  OF THE GEARS            "
  SET PRNPLT=.F.,CALPLT=.F.,STRPLT=.T.,GRDSPL=.T.,YINSPL=1.0
  PLOT "XAXIS"=T,"XTAG"="(SEC)",W1,W2,W3,"TAG"="(RAD/SEC)"
END
PROCED CC
  SET TITLE="ANGLES OF ROTATION,GEAR 1 AND GEAR 2          "
   SETPRNPLT=.F.,CALPLT=.F.,STRPLT=.T.,GRDSPL=.T.,YINSPL=2.0,YASSP
                  L=.25
  PLOT "XAXIS"=T,"XTAG"="(SEC)",THETA1,THETA2,"TAG"="DEG"
END
PROCED DD
  SET TITLE="ANGLE FLYWHEEL,ANGLE OF TWIST(SHAFT)         "
   SETPRNPLT=.F.,CALPLT=.F.,STRPLT=.T.,GRDSPL=.T.,YINSPL=2.0,YASSP
                  L=.25
  PLOT "XAXIS"=T,"XTAG"="(SEC)",TWIST,THETA3,"TAG"="DEG"
END
PROCED EE
  SET CALPLT=.F.,STRPLT=.T.,GRDSPL=.T.,TTLSPL=.T.,YINSPL=1.0
  SET TITLE="FORCE BETWEEN GEAR TEETH                     "
  PLOT "XAXIS"=Q5,"XTAG"="in",F,"TAG"="lb"
END
PROCED FF
  SET CALPLT=.F.,STRPLT=.T.,GRDSPL=.T.,TTLSPL=.T.,YINSPL=1.0
  SET TITLE="DISPLACEMENT BETWEEN GEAR TEETH              "
  PLOT "XAXIS"=T,"XTAG"="(SEC)",Q5,"TAG"="IN"
END
PROCED GG
  SET CALPLT=.F.,STRPLT=.T.,GRDSPL=.T.,TTLSPL=.T.,YINSPL=1.0
  SET TITLE="INPUT TORQUE                                 "
  PLOT "XAXIS"=T,"XTAG"="(SEC)",SE1,"TAG"="LB-FT"
END
PROCED HH
```

```
  SETCALPLT=.F.,STRPLT=.T.,GRDSPL=.T.,TTLSPL=.T.,YINSPL=2.0,YASSP
                          L=.25
 SET TITLE="TORQUE ON GEAR1 AND ON SHAFT                    "
  PLOT"XAXIS"=T,"XTAG"="(SEC)",E2,"TAG"="LB-FT",E10,"TAG"="LB-FT
                             "
END
SET CMD=DIS

STOP
```

The plots are generated by entering the AA, BB, CC, DD, EE, FF, GG, HH labels at the ACSL> prompt. The prompt will appear as soon as each plot is completed.

DESIGN CRITERIA

The contact force between teeth depends upon the relative position of the gears due to the slack between them.   The contact force is zero in position where the teeth are not in contact but increases proportionally to the displacement after contact has been made. Using this nonlinear relation and a cyclic input torque, it is important to find the torques generated internally on the gears and the shaft due to the dynamics of the system.

It is necessary to find values and graphical plots for the design variables such as angles, angular velocities, accelerations and the dynamic forces acting on the different components.   These will assist the designer to prevent fatigue failure because now the stress levels can be calculated. The position of the gears is important to calculate as knowledge of the angular displacements can assist in satisfying geometric constraints and determining the acceptable backlash.

RESULTS

The results of the calculations are shown in the following figures. They show plots of the angular velocities, angular accelerations and torques and all other design variables of interest established in the design criteria. Show below is a set of these variables for the parameters given.

It is possible to study different parameter values interactively without modifying the input file and using run time commands in order to try several designs. Other variables can be calculated or plotted besides the ones explained in the design criteria and plotted below because CAMPG has generated all internal variables and all were calculated as a result. When changes are made interactively, all interactive commands of the ACSL program can be used to analyze the system.

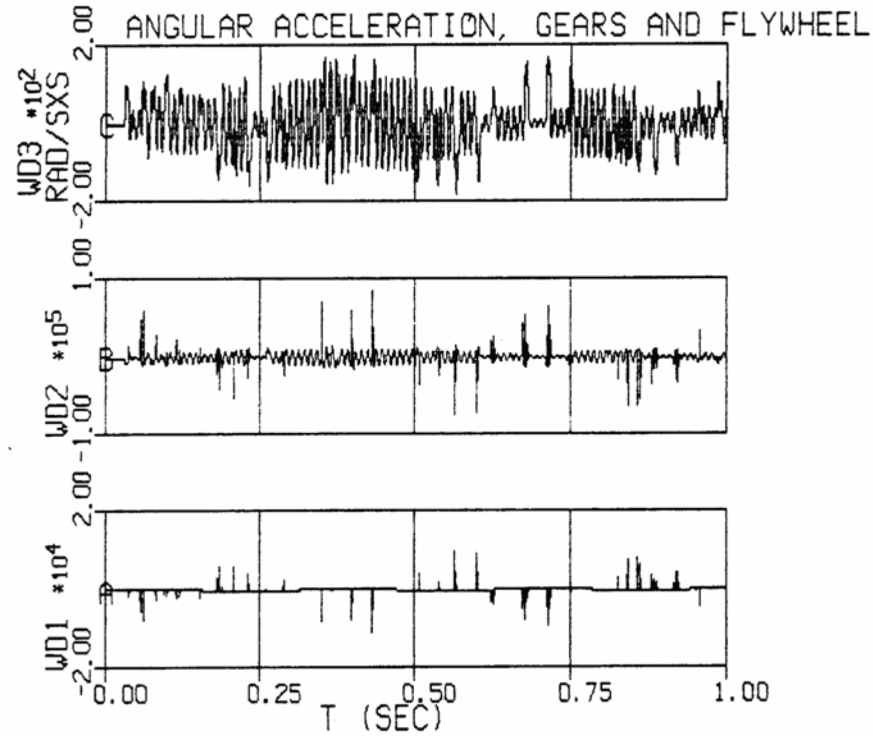


Fig. 4-22 Angular Acceleration

Fig 4-23 Angles Response.

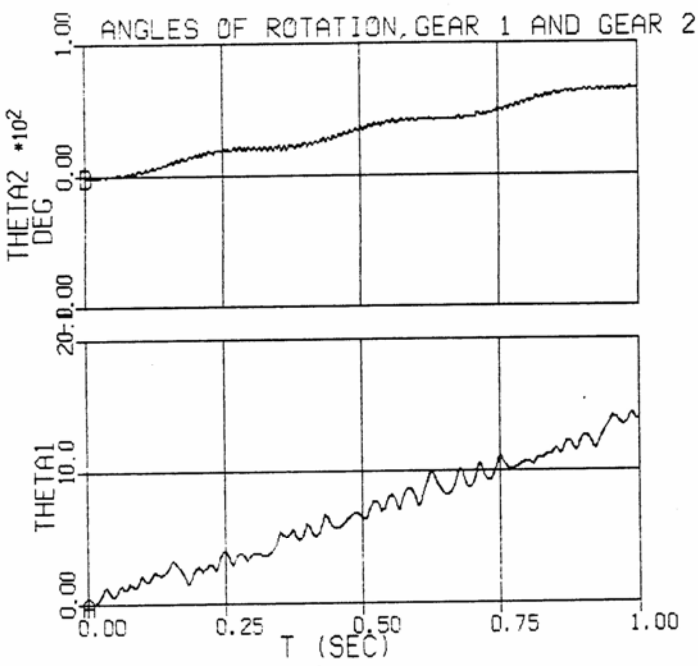


Fig 4-24
Angle flywheel
Angle of Twist

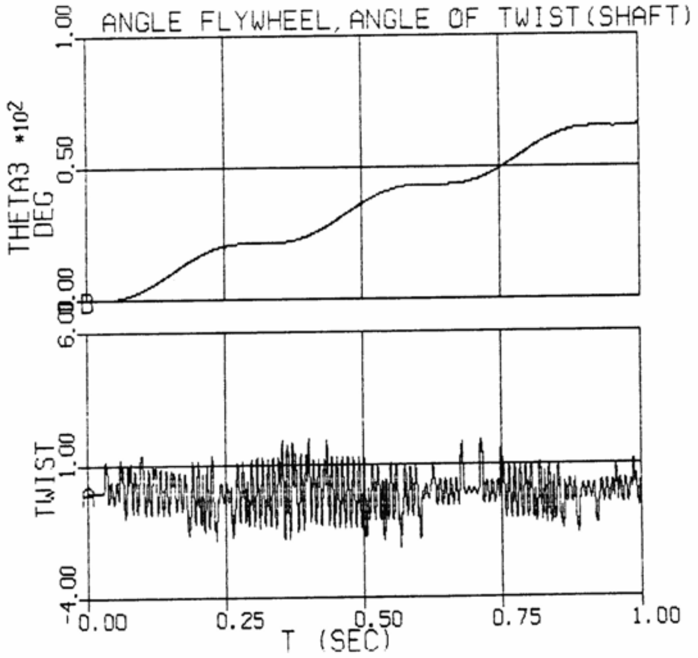


Fig. 4-22 - Since the input is a torque; a causal effect is the acceleration and velocity of the gears. These variables are affected by de discontinuity of the contact made among the gear teeth. The plot at the bottom of *Fig. 4-22* shows that gear 1 is accelerating under a basic harmonic function but the positive and negative peaks are accelerations of decelerations due to the dynamics of the gear train. The figure in the middle is an order of magnitude bigger and contains higher peeks of acceleration and deceleration. This can be explained due to several factors. The most influential ones are the gear ratio and the separations and sudden contact that the gears experience at a high frequency. The acceleration at the flywheel is affected by the stiffness of the shaft; it is lower in this case because the shaft is flexible.

Fig 4-23 - This figure shows the angular velocity of the gears and also of the flywheel. The bottom figure shows a nonlinear function while the flywheel velocity appears as a periodic function. The changes in velocity of gear 2 occur at a high frequency. This is due to the vibration of the gear train on both sides of gear 3. Rapid changes in the motion of gear 1 and the backlash between gear teeth. The influence of the compliant shaft is seen in the plot of the angular velocity of the flywheel (top plot). Changes are smoother in the shaft velocity since this is a capacitive element and therefore stores energy. Mathematically this element performs integration of W3 and therefore eliminates the noise seen in that function. This change is obvious between WD3 in *Fig. 4-22* and W3 in *Fig. 4-23*.

Figure 4-24 - This figure compares the position angle of rotation of the gears and the angle of twist of the shaft. It shows the geometrical configuration of the gear train. It can be seen from this figure how the gear train starts to move in one direction while the angle of twist in the shaft changes to +2 to -2 degrees.

Fig 4-25
Angle flywheel
Angle of Twist

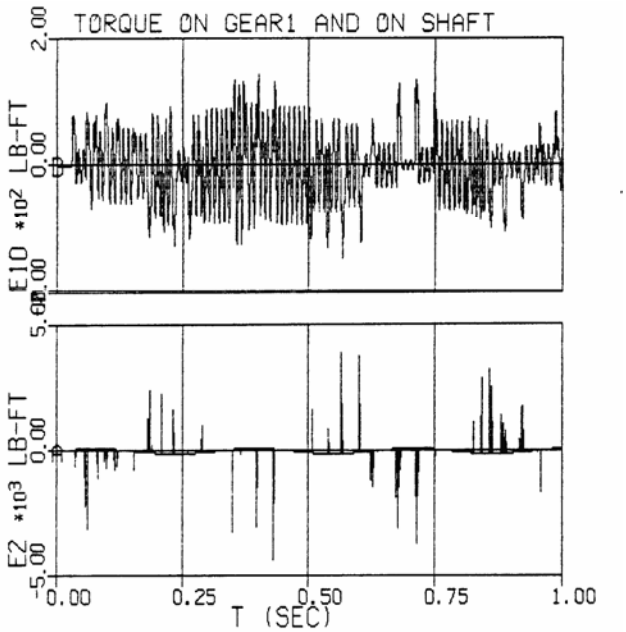


Fig. 4-25 - Shows the torque at the input gear. This plot is similar to the one of the acceleration. The relationship can be explained by Newton's Law in rotation since the rotational moment of inertia is the relational constant. Therefore the torque is proportional to the angular acceleration of gear 1. *Fig. 4-24.* gives a good understanding of the stress level changes within the shaft and therefore can be used to design the shaft.

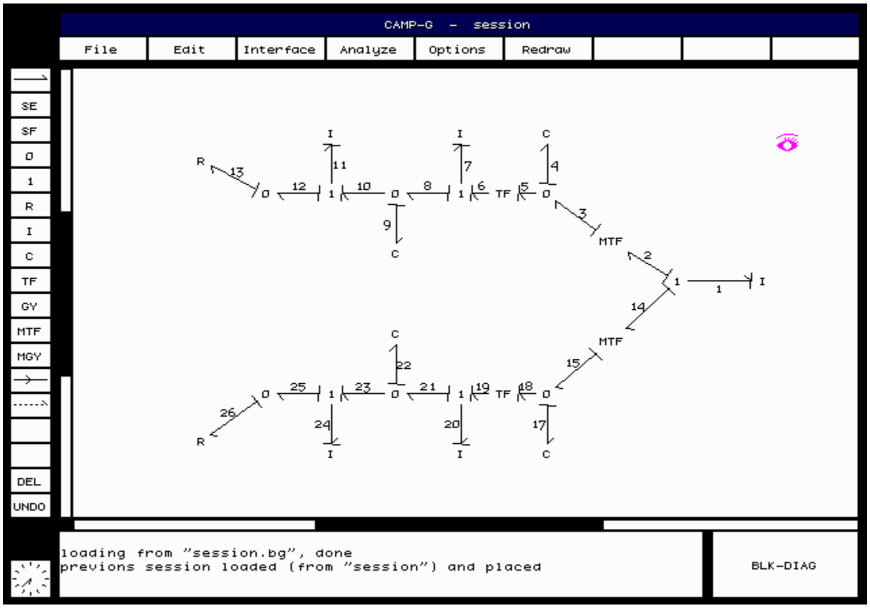
Chapter 5

Advanced Features

5.1 Advanced Menu Features

EXPLAIN

Explain is the first item located under the “Analyze” menu. The purpose of this option is to explain any problems with the bond graph. This is used when the bond graph has a problem and the user cannot determine the problem, this can be used as a tool in helping determine the problem. When this option is invoked the cursor changes to a stethoscope. The user simply needs to click on the bond graph element, junction or bond to see an explanation of the problem. The explanation will appear in the message box. For an example of this see the following picture, *Fig. 5-1.*.

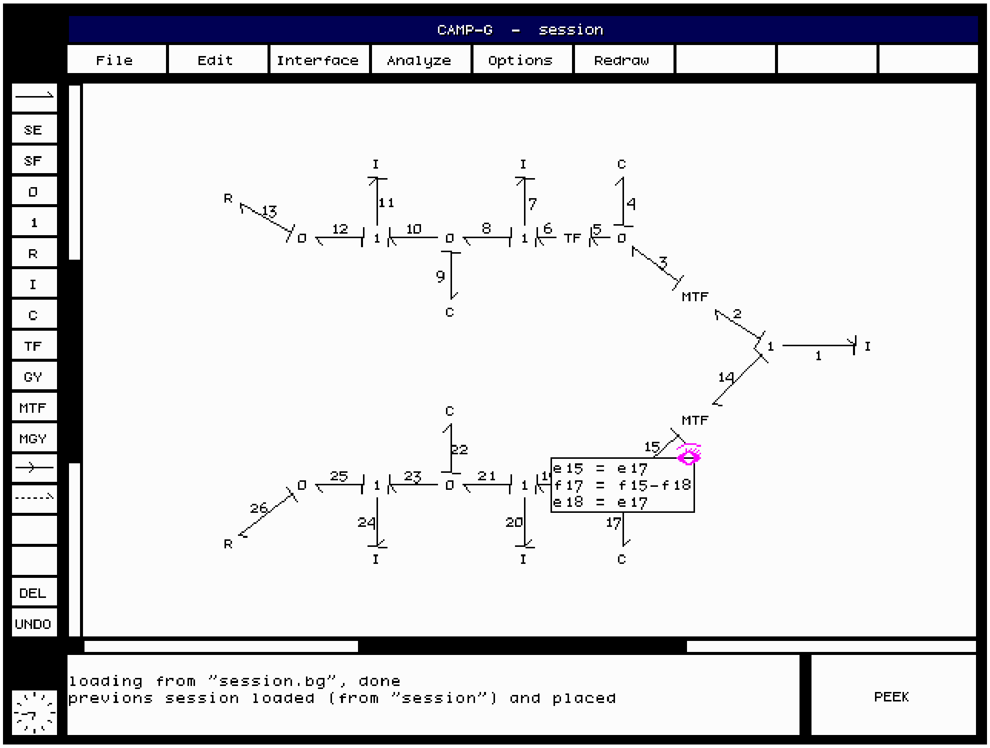


```
loading from "session.bg", done
previons session loaded (from "session") and placed
```

Fig 5.1 Non-linear hydraulic-mechanical system

PEEK

Peek is the second item located under the “Analyze” menu. The purpose of this option is to view the equations of the particular element, junction or bond that is being picked. When this menu option is chosen, the icon changes to look like an eye. The user simply needs to click on a bond graph element, junction or bond and the equations for it will be displayed. For an example of this see the following picture, *Fig. 5-2.*



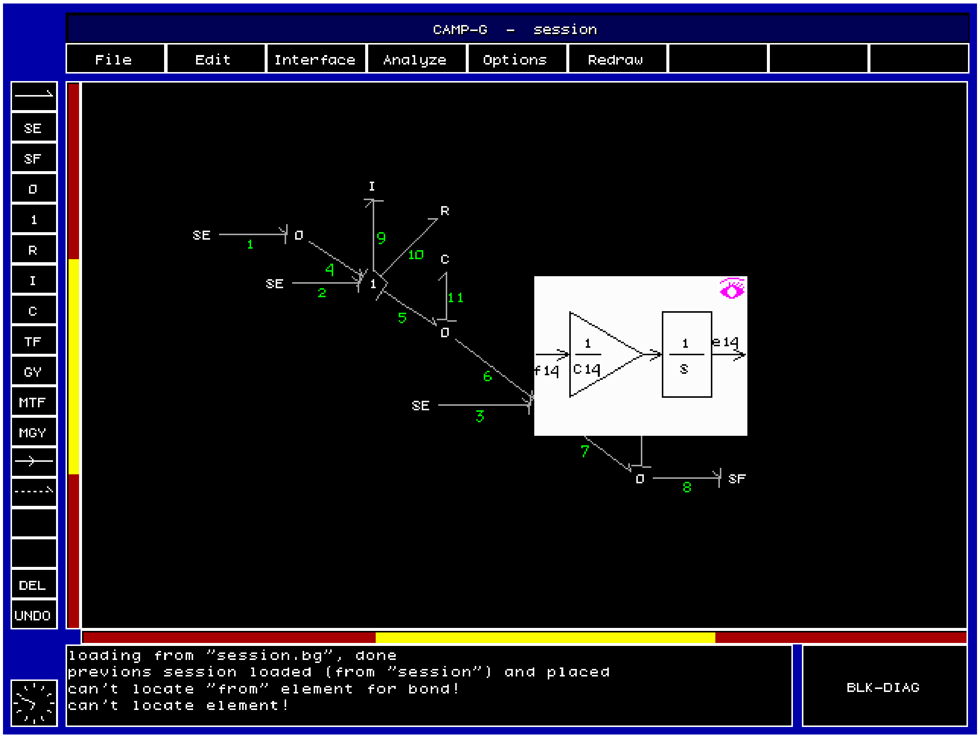
```
e15  =  e17
f17  =  f15-f18
e18  =  e17
```

```
loading from "session.bg", done
previons session loaded (from "session") and placed
```

Fig 5-2 PEEK display

BLK-DIAG

Blk-Diag is the third item located under the “Analyze” menu. The purpose of this option is to view the block diagram that corresponds to the individual elements and junctions. When this option is invoked, the icon turns to the same eye as it does when Peek is used. Once again, the user simply needs click on the element or the junction to see a block diagram representation of that element or junction. For an example of this see the following picture, *Fig. 5-3.* .



```
loading from "session.bg", done
previons session loaded (from "session") and placed
can't locate "from" element for bond!
can't locate element!
```

Fig. 5-3 Simulink equivalent blocks for the Bond Graph Elements.

5.2 User Preference Settings

STICKY

Sticky is located first under the “Options” menu. Sticky is used to keep an option on. When Sticky is set to “On”, any menu item or bond graph element that is used will continue to be available until the user changes to another menu item or bond graph element.

GRID

Grid is located second under the “Options” menu. With this option, the user can turn the grid on and off as well as hide the grid.

FUNCTIONS

Functions is located third under the “Options” menu. This indicates that Sources are not constants.

DISPLAY MODE

Display Mode is located fourth under the “Options” menu. This option is used to switch the display from color to black and white. This allows the user to print the screen with older printers and have the print come out with much greater quality.

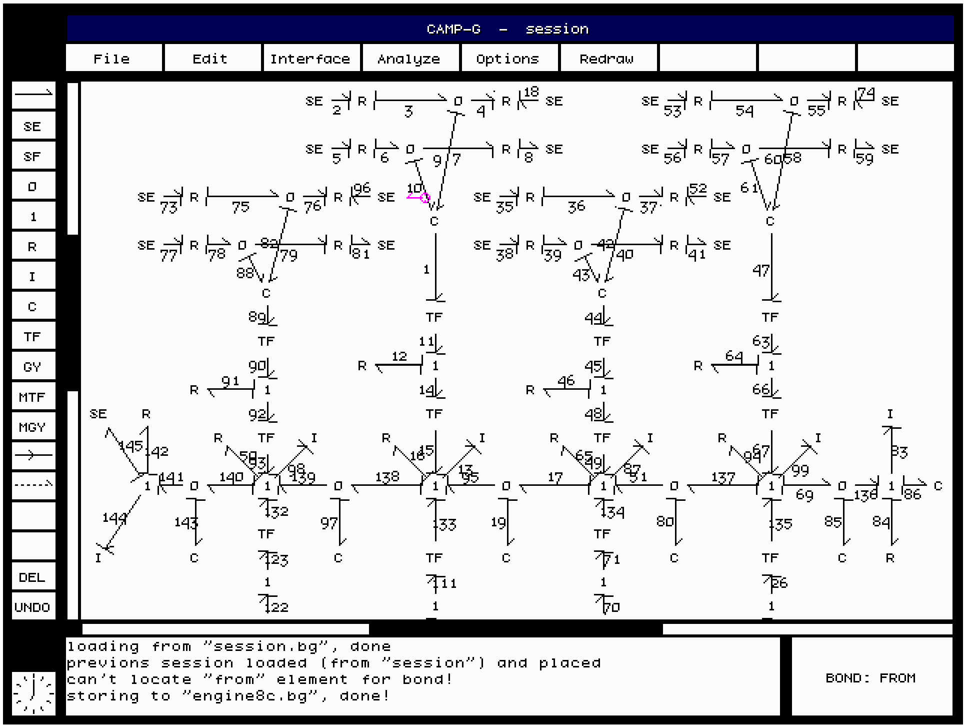
COLOUR

Colour is located fifth under the “Options” menu. With this option, the user can change the color of different aspects of the CAMPG display to match the user’s preferences. The user has the option of changing the color of the Bond, Element, Number, Marked, Grid, Ambig, Deriv, and Others. This really allows the user to customize the CAMPG display.

5.3 Advanced Bond Graph Features

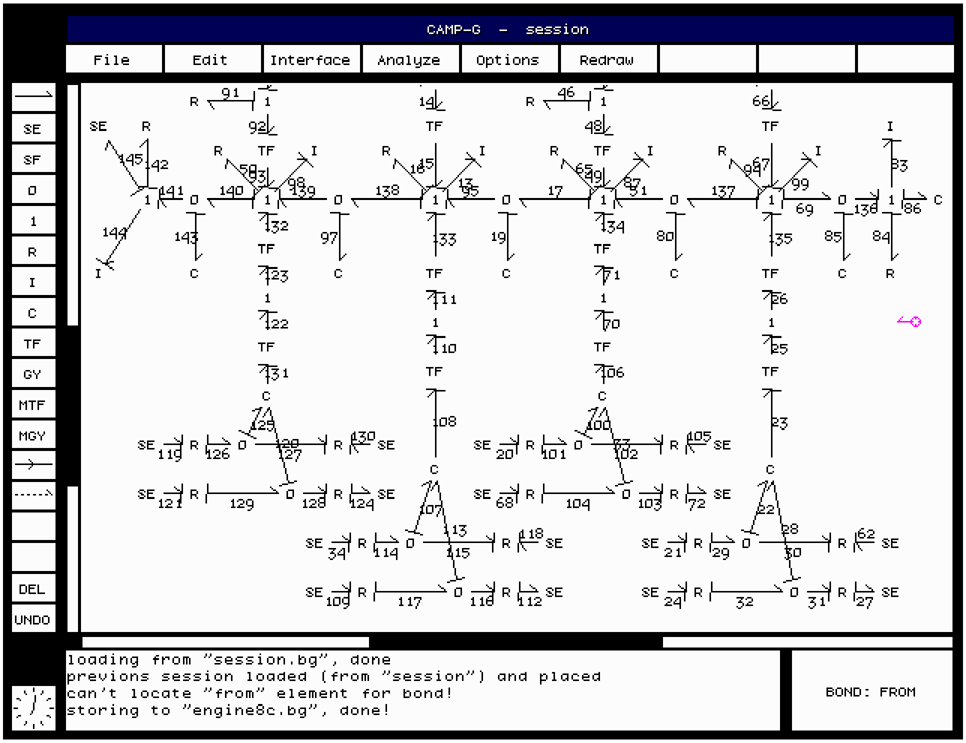
LARGE BOND GRAPHS

CAMPG allows the user to create very large bond graphs inside the workspace by being able to scroll up/down and left/right. This allows the user to create bond graphs that are much larger than the viewable area. This is very useful in many applications in that many applications have bond graphs that are very large. An example of this can be seen in the following *Fig. 5-4 and Fig.5-5.*



```
loading from "session.bg", done
previons session loaded (from "session") and placed
can't locate "from" element for bond!
storing to "engine8c.bg", done!
```

Fig 5-4 Four cycle internal combustion engine bond graph.



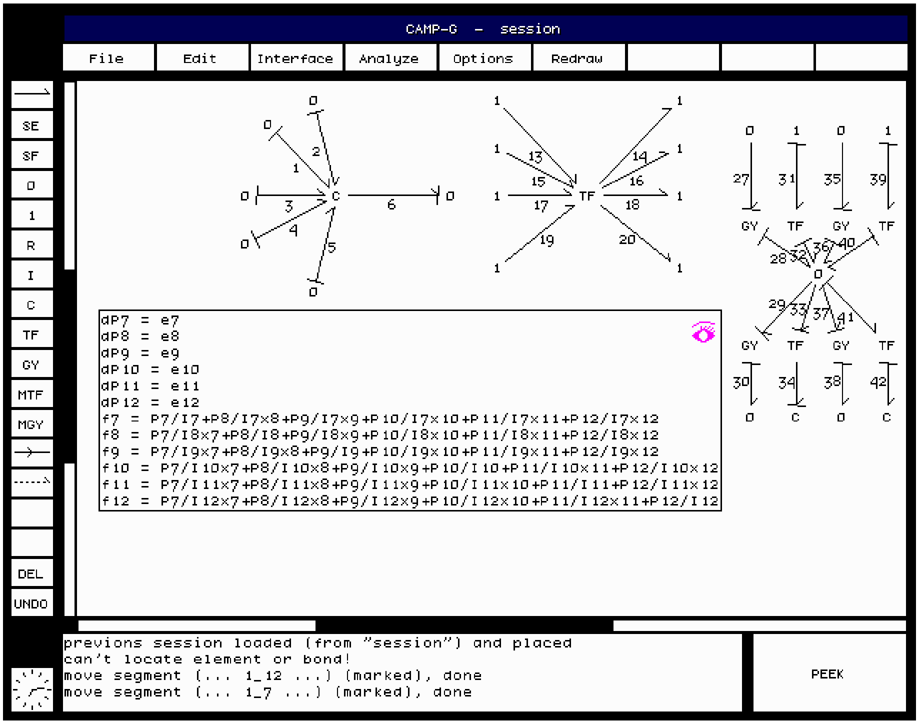
```
loading from "session.bg", done
previons session loaded (from "session") and placed
can't locate "from" element for bond!
storing to "engine8c.bg", done!
```

BOND: FROM

Fig 5-5 Eight cylinder engine CAMPG model

MULTIPORT ELEMENTS

CAMPG allows the user to create multiport elements and use these elements in bond graphs. This is also a very useful feature in many real world applications in that many bond graphs of real world applications make use of multiport elements. CAMPG has the ability to display them and when an interface has been selected, it also has the ability to compute the equations for them. A few examples of the multiport element can be seen in *Fig. 5-6*, along with the complex equations for one of the multiport elements.



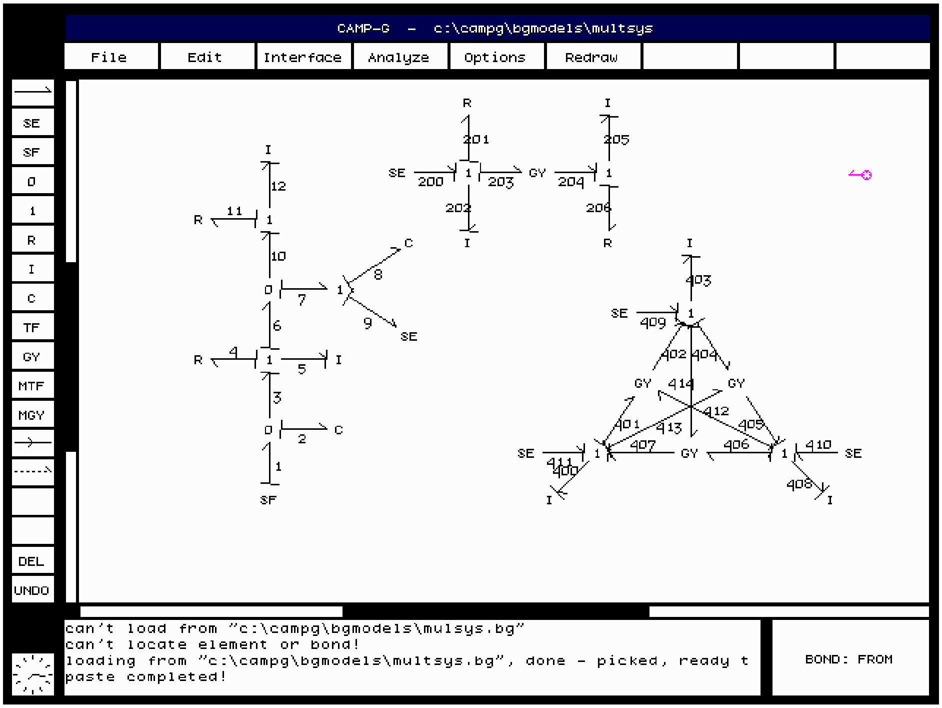
```
dP7 = e7
dP8 = e8
dP9 = e9
dP10 = e10
dP11 = e11
dP12 = e12
f7 = P7/I7+P8/I7x8+P9/I7x9+P10/I7x10+P11/I7x11+P12/I7x12
f8 = P7/I8x7+P8/I8+P9/I8x9+P10/I8x10+P11/I8x11+P12/I8x12
f9 = P7/I9x7+P8/I9x8+P9/I9+P10/I9x10+P11/I9x11+P12/I9x12
f10 = P7/I10x7+P8/I10x8+P9/I10x9+P10/I10+P11/I10x11+P12/I10x12
f11 = P7/I11x7+P8/I11x8+P9/I11x9+P10/I11x10+P11/I11+P12/I11x12
f12 = P7/I12x7+P8/I12x8+P9/I12x9+P10/I12x10+P11/I12x11+P12/I12
```

```
previons session loaded (from "session") and placed
can't locate element or bond!
move segment (... 1_12 ...) (marked), done
move segment (... 1_7 ...) (marked), done
```

Fig 5-6 Complex multiports, fields

USER CONTROLLED NUMBERING

The user has the option of specifying the number of the bond graph bonds. This can be very useful when creating bond graphs for a system that has several bond graphs that are all used to create a complete simulation, but are not connected to each other as far as the bond graph is concerned. This way the user can create the bond graphs individually and then control the numbering so when the equations are all put together, there are no elements or bonds with the same name. It is recommended that the user create all the bond graphs for a single system, if the system consists of more than one bond graph, in the same CAMPG bond graph model. This way all the equation will automatically be incorporated into the files that are created when an interface is chosen. See *Fig. 5-7* for an example of this.



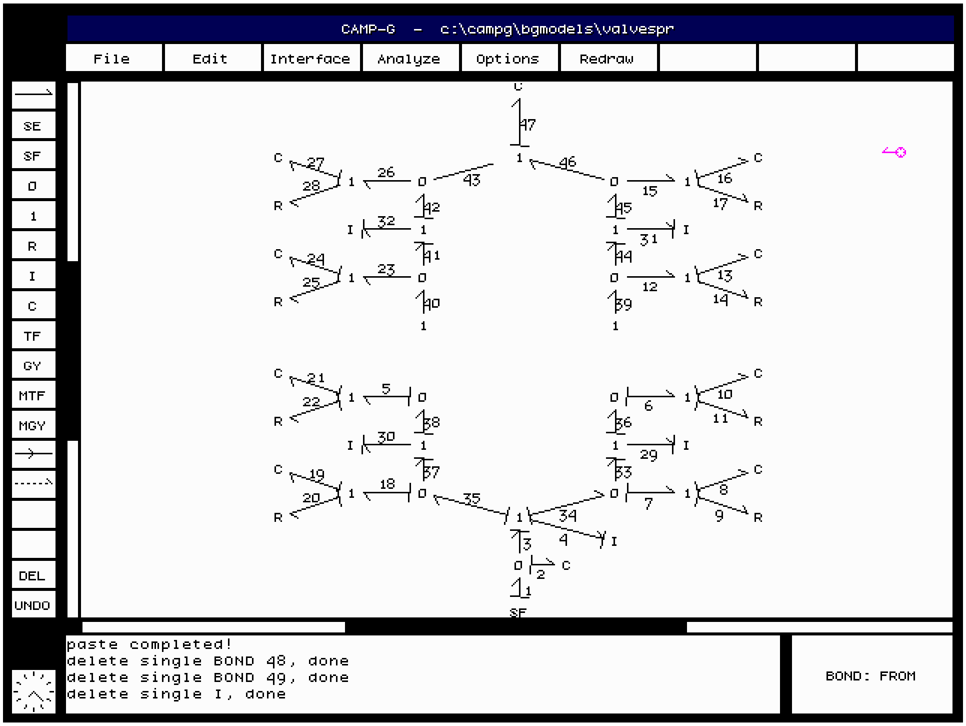
```
can't load from "c:\campg\bgmodels\mulsys.bg"
can't locate element or bond!
loading from "c:\campg\bgmodels\multsys.bg", done - picked, ready t
paste completed!
```

```
BOND: FROM
```

Fig 5-7 Bond Graph renumbering option

AUTOMATIC CAUSALITY DETECTION

CAMPG automatically detects if there are any causality problems in a bond graph. If there are problems, the bond graph in the CAMPG display will show where the problems exist by displaying the bonds, elements and junctions in a different color than normal. This color is set to Red as the default color, but the user can define what they want this color to be by changing the color settings as described in **COLOUR** from above. See *Fig. 5-6* for an example of this. When the system has determined a causality problem, the user can use the Explain option as described in **EXPLAIN** from above to help determine the cause of the problem.

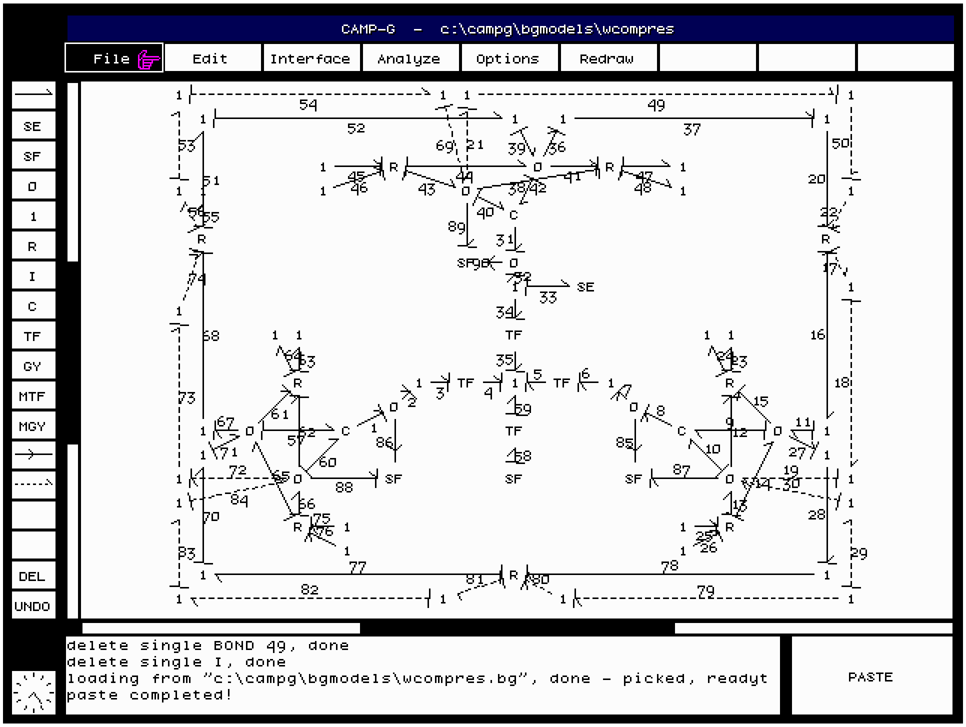


```
paste completed!
delete single BOND 48, done
delete single BOND 49, done
delete single I, done
```

Fig 5-6 Large Bond Graph Model

PSEUDO BOND GRAPHS

Pseudo bond graphs can be created simply to help the user understand the system better and to get a better understanding of everything that will be involved in modeling the system. An example of this can be seen in *Fig. 5-7*.

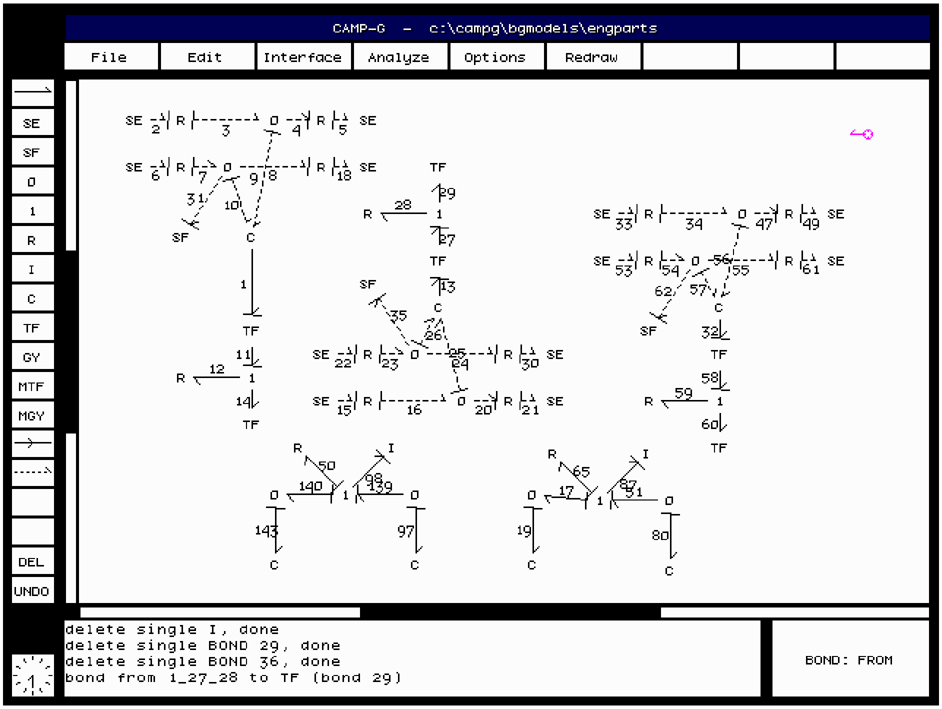


```
delete single BOND 49, done
delete single I, done
loading from "c:\campg\bgmodels\wcompres.bg", done - picked, readyt
paste completed!
```

Fig. 5-7 Use of Pseudo bond graphs

COPY AND FLIP BOND GRAPH STRUCTURES

In many cases, in a real system there are several parts, which are identical to each other. Normally the user would have to create duplicate parts of the bond graph manually. When using CAMPG, the user has the option of simply copying and/or flipping selected segments of elements, junctions and/or bonds. This shortens the time required to create the bond graph. An example of this can been seen in *Fig. 5-8*.



```
delete single I, done
delete single BOND 29, done
delete single BOND 36, done
bond from 1_27_28 to TF (bond 29)
```

BOND: FROM

Fig 5-8 Complex system components

SUBSYSTEMS

Several Bond Graph models can be created independently on the same screen or subsystems existing on .bg files on disk can be imported into the working screen. Subsystems can be numbered differently using the renumber option on the EDIT menu.

SIMULTANEOUS SIMULATIONS

Using CAMPG's ability to create separate bond graphs is the same session window; it is possible to run simultaneous simulations. This can be useful if the user needs to compare the simulation results of two systems that are being compared. To illustrate this technique, two completely unrelated systems will be modeled simultaneously; this will help to demonstrate the flexibility of this procedure. What this will do is create one set of simulation files, but with two different dynamic systems represented in the one set of simulation files. To make the distinction between the two separate systems, some of the techniques that are described above will be implemented in this example. For example, the user controlled numbering will be used to create a gap in the numbering of the bond graphs and therefore distinction between the two systems.

EXAMPLE:

In this example, it is going to be demonstrated how the user can run one simulation that represents two different dynamic system. Both of the systems that are demonstrated in this example are discussed in detail in chapters two and three. For more in depth detail on either of these two systems, see either chapter two or three. The two dynamic systems that are going to be used again are the example of the Crash Test and the Hydroelectric Power Plant. Pictures of both the physical systems are seen in *Fig. 5-9 and Fig. 5-10.*

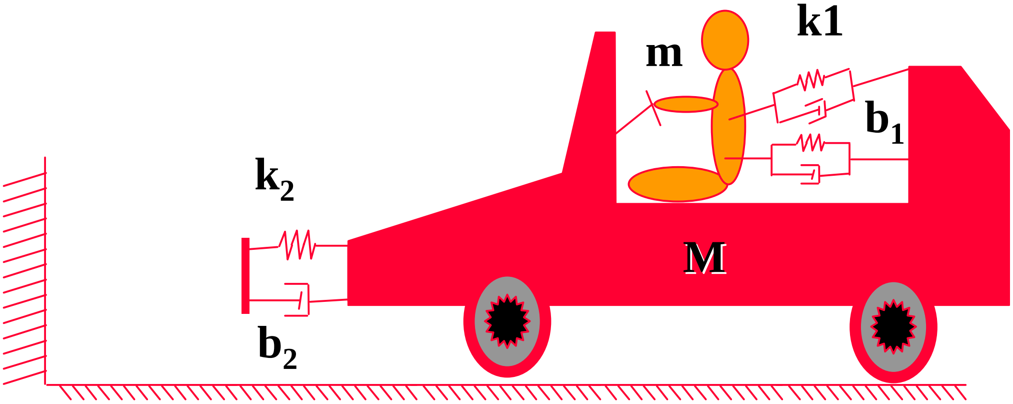


Fig. 5-9 Physical System of Dummy in Car

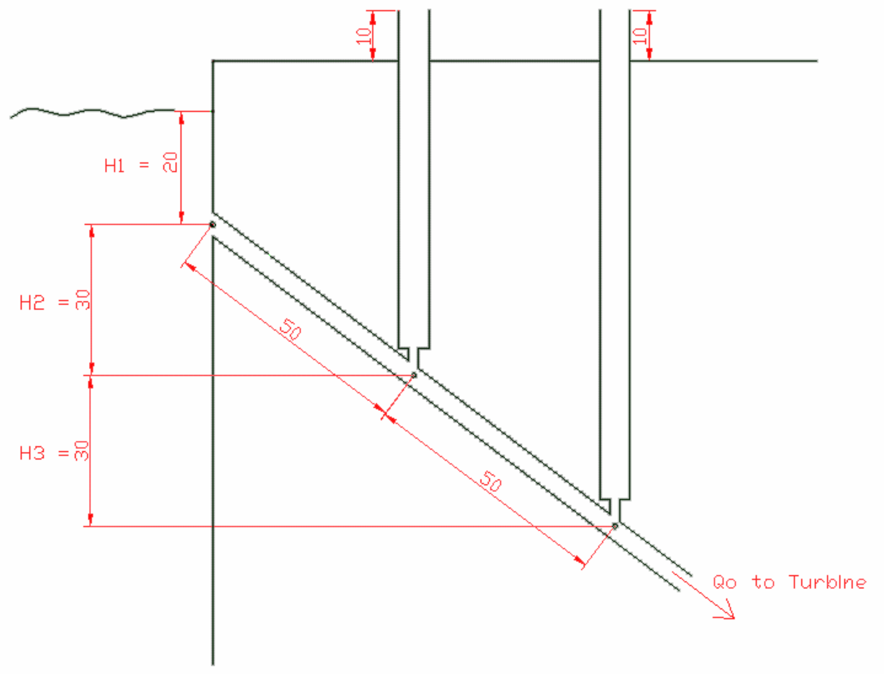
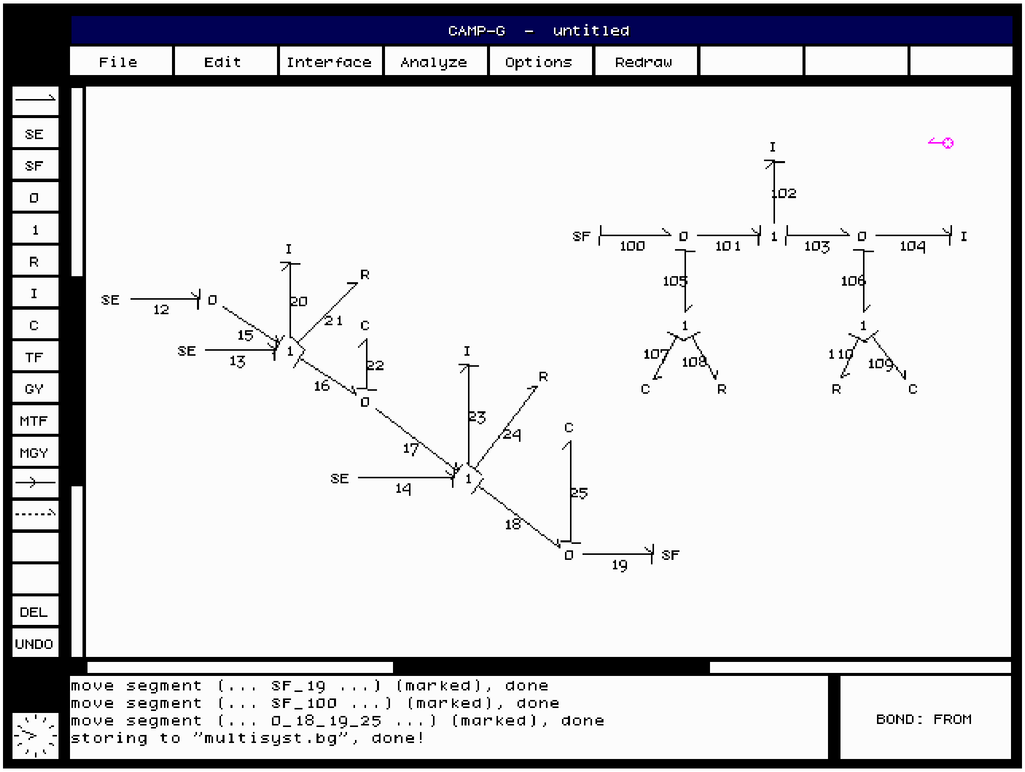


Fig 5-10 Physical System of Hydroelectric Power Plant

Seen below, in *Fig. 5-11* are the bond graphs of the two systems in the same CAMPG session window. This window is interfaced with Matlab and the three files, CAMPGMOD, CAMPGEQU, and CAMPGSYM are created. In this example, only the first two of the three files are going to be used.

Bond Graphs of Both Systems



```
move segment (... SF_19 ...) (marked), done
move segment (... SF_100 ...) (marked), done
move segment (... 0_18_19_25 ...) (marked), done
storing to "multisyst.bg", done!
```

Fig 5-11 Simultaneous Simulation of two unrelated systems

In the file called CAMPGEQU, notice the differential equations that describe the two systems. Notice the two systems are both described in the set of equations, and also notice that since we used the user definable numbering in CAMPG that indeed the set of equations represents both dynamic systems.

Listing of CAMPGMOD.M

```
%......CAMPGMOD.M - MATLAB MODEL INPUT FILE  ......
 clear
 r=.3;
 A=pi*r^2;
 % ......  Initial conditions  ........
```

```
              P9IN= 0 ; P12IN= 0 ;
              Q11IN= 0 ; Q14IN= 0 ;
              P102IN= 16763.96 ; P104IN= 1117.6 ;
              Q107IN= 0 ; Q109IN= 0 ;
   initial = [Q11IN; Q14IN; Q109IN; Q107IN; P9IN; P12IN; P104IN;
P102IN] ;
 % ......System Physical Parameters........
 global I9 R10 C11 I12 R13 C14 I102 I104 C107 R108 C109 R110
 global Efforts counter
              I9 = 1000*50/.1 ;  R10 = 100000 ;
              C11 = A/(1000*9.8) ;  I12 = 1000*50/.1 ;
              R13 = 100000 ;  C14 = A/(1000*9.8) ;
              I102 = 1500 ;  I104 = 100 ;
              C107 = 1/300000 ;  R108 = 80000 ;
              C109 = 1/10000 ;  R110 = 500 ;
 % ...... External inputs se(t), sf(t) ......
   global SE1 SE2 SE3 SF8 SF100
              SE1 = 1000*9.8*20 ;
              SE2 = 1000*9.8*20 ;
              SE3 = 1000*9.8*20 ;
              %SF8 = ?? ;  Will be defined in CAMPGEQU file
              SF100 = 0 ;
 %..... Simulation Time Control .....
              t0= 0 ;   %  Initial Time
              tf= 200 ;   %  Final Time
              tspan= [t0 tf];
 % ......  Computer Simulation ......
 %  Solution of system equations using Matlab "ode23" function
 %  The campgequ.m function contains the system differential
 %  equations in state variable form.
 %
 %  It returns the vector [t,p-q] where:
 %  t = time and p-q = vector of state variables
 %  [t,p_q] = ode23('campgequ',t0,tf,initial);
    counter=1;
     status = odeset('outputfcn','esandfs');
    [t,p_q] = ode23('campgequ',tspan,initial,status);
 %          Q11= p_q(1) ; %          Q14= p_q(2) ;
 %          Q109= p_q(3) ; %          Q107= p_q(4) ;
 %          P9= p_q(5) ; %          P12= p_q(6) ;
 %          P104= p_q(7) ; %          P102= p_q(8) ;
 % State variables vector
 % p_q = [Q11; Q14; Q109; Q107; P9; P12; P104; P102] ;
 %%Plotting stuff for the Hydroelectric Power Plant
```

```
   figure(1)
   subplot (211),plot(t,p_q(:,1)/A,'b'),grid,axis([0 200 0 60])
   title('Height in shorter Surge Tank'),
   subplot (212),plot(t,p_q(:,2)/A,'m'),grid,axis([0 200 0 90])
   title('Height in taller Surge Tank')
   figure(2)
   subplot (211),plot(t,Efforts(:,1)*-1,'b'),grid
   title('Pressure in upper segment of standpipe')
   subplot (212),plot(t,Efforts(:,2)*-1,'m'),grid,zoom
   title('Pressure in upper segment of standpipe')
%%Plotting stuff for the Crash Test
   figure(3)
   plot(t,p_q(:,3),'r'),grid,xlim([0,1]);
   title('Distance the Dummy''s head travels')
   ylabel ('Distance (meters)'),xlabel('Time (seconds)')
   figure(4)
   plot (t,Efforts(:,3),'r'),grid,xlim([0,1]);
   title('Force Acting on the Dummy')
   ylabel('Force (N)'), xlabel('Time (seconds)')
```

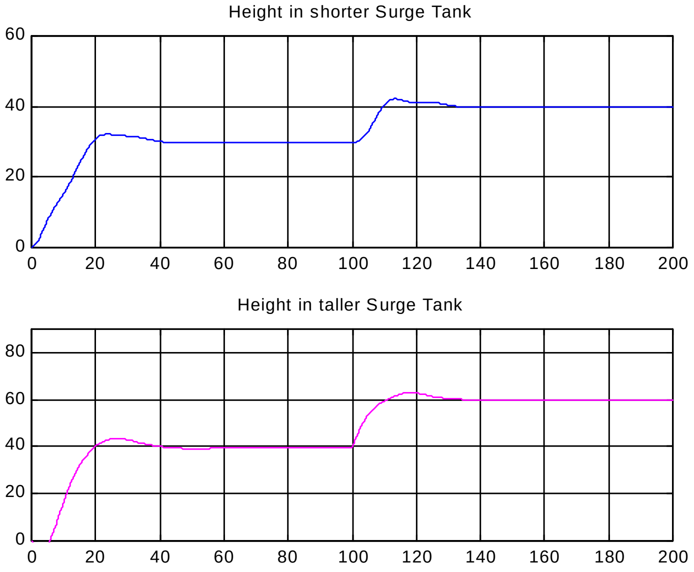
Listing of CAMPGEQU.M

```
   function p_qdot = campgequ(t,p_q)
 %  ...........campgequ.m   CAMPG/MATLAB function ...........
 %  System differential equations, state Vectors
 %
   global I9 R10 C11 I12 R13 C14 I102 I104 C107 R108 C109 R110
   global SE1 SE2 SE3 SF8 SF100 vect_out
   if t < 100
      SF8=1;
   elseif t >= 100 & t <= 100.1
      SF8=-10*t+1000;
   else
      SF8=0;
   end
 % System Differential Equations-First Order Form
 %...... Define State Variables ......
         Q11= p_q(1) ;          Q14= p_q(2) ;
         Q109= p_q(3) ;          Q107= p_q(4) ;
         P9= p_q(5) ;          P12= p_q(6) ;
         P104= p_q(7) ;          P102= p_q(8) ;
 % State variables vector
   % p_q = [Q11; Q14; Q109; Q107; P9; P12; P104; P102] ;
 %...... Define derivatives (dp,dq) and output variables (e,f) .
         e1=SE1 ;                            e2=SE2 ;
```

```
        f9=P9/I9 ;                  e3=SE3 ;
        f12=P12/I12 ;               e4=e1 ;
        e11=Q11/C11 ;               f5=f9 ;
        e6=e11 ;                    f6=f12 ;
        e14=Q14/C14 ;               f7=f12 ;
        e8=e14 ;                    f8=SF8 ;
        f10=f9 ;                    f11=f5-f6 ;
        f13=f12 ;                   f14=f7-f8 ;
        f100=SF100 ;                f102=P102/I102 ;
        f103=f102 ;                 f104=P104/I104 ;
        e107=Q107/C107 ;            e109=Q109/C109 ;
        f106=f103-f104 ;            f109=f106 ;
        f110=f106 ;               dQ11=f11 ;
      dQ14=f14 ;                  dQ109=f109 ;
        f4=f9 ;                     f2=f9 ;
        f3=f12 ;                    e5=e11 ;
        e7=e14 ;                    e10=f10*R10 ;
        e13=f13*R13 ;               f101=f102 ;
        f105=f100-f101 ;            e110=f110*R110 ;
        f107=f105 ;                 f108=f105 ;
      dQ107=f107 ;                  f1=f4 ;
        e9=e2+e4-e5-e10 ;           e12=e3+e6-e7-e13 ;
        e106=e109+e110 ;            e104=e106 ;
        e108=f108*R108 ;          dP9=e9 ;
      dP12=e12 ;                  dP104=e104 ;
        e105=e107+e108 ;            e101=e105 ;
        e103=e106 ;                 e100=e105 ;
        e102=e101-e103 ;          dP102=e102 ;
% ... Build vector of derivatives p_qdot(n)...
%        p_qdot1) = dQ11 ; %       p_qdot2) = dQ14 ;
%        p_qdot3) = dQ109 ; %       p_qdot4) = dQ107 ;
%        p_qdot5) = dP9 ; %       p_qdot6) = dP12 ;
%        p_qdot7) = dP104 ; %       p_qdot8) = dP102 ;
% Derivatives vector
  p_qdot = [dQ11; dQ14; dQ109; dQ107; dP9; dP12; dP104; dP102];

        vect_out=[e9,e12,e104];
```

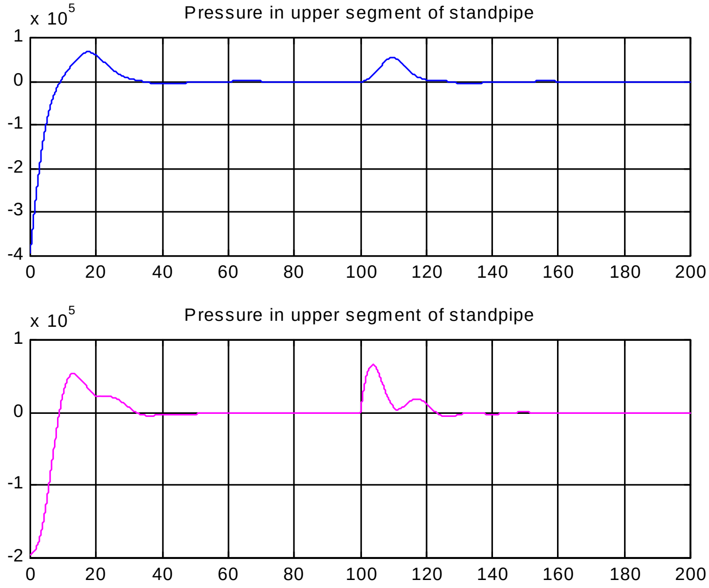
Results

What follows are the graphs that are output from the two previous files. As will be seen, the graphs that are seen below match the graphs fro these systems when they are modeled separately as in the examples in chapters two and three.


Height in shorter Surge Tank

Height in taller Surge Tank

Fig. 5-12 Simulation Results of Simultaneous Simulation


Pressure in upper segment of standpipe

Pressure in upper segment of standpipe

Fig. 5-13 Simulation Results of Simultaneous Simulation

Fig 5-14
Crash test model simultaneously computed

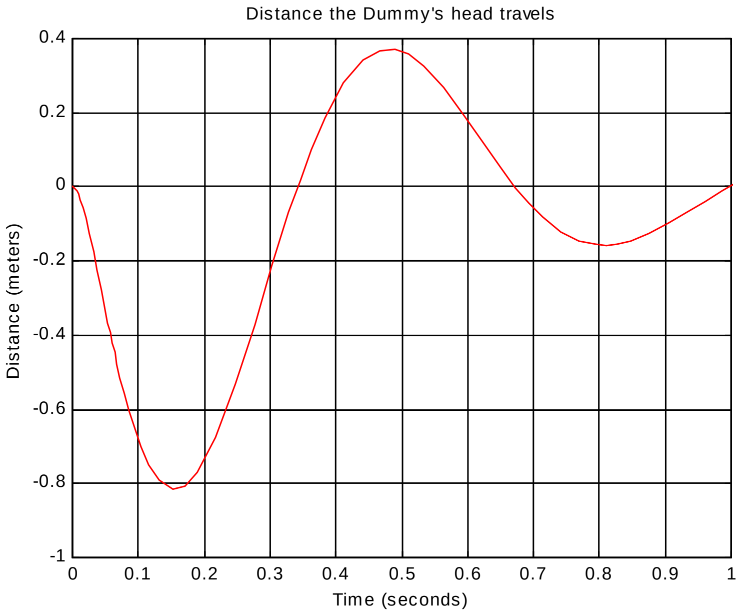
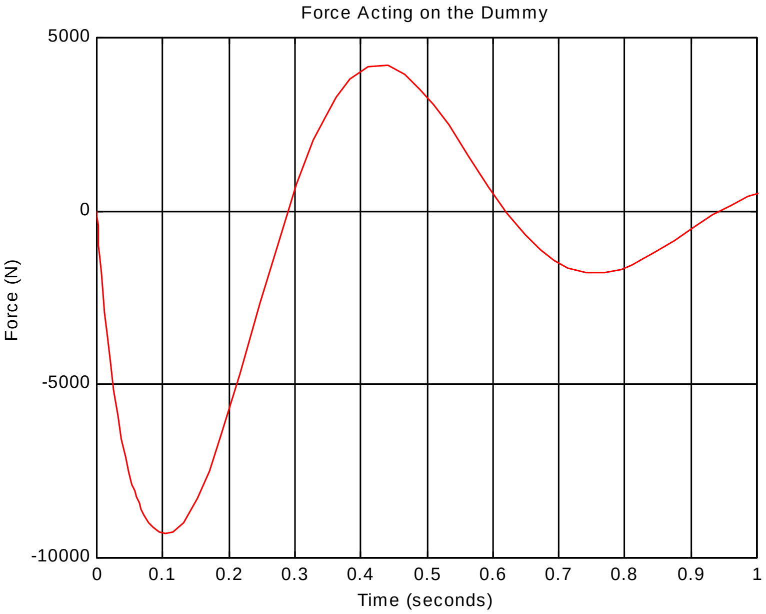


Fig 5-14
Crash test model simultaneously computed



Technical References

BOOKS:

1. J. J. Granda and F. E. Cellier, eds. "Proceedings of ICBGM'2007. 8th International Conference on Bond Graph Modeling and Simulation“ Simulation Series, Vol 39 Nr 1, SCS Publishing, ISBN: 1-56555-310-1 January 2007.

2. Karnopp, D., Rosenberg, R., SYSTEM DYNAMICS. Modeling and Simulation of Mechatronics Systems. Wiley and Sons, New York, 2006.

3. MATLAB User's Manual. The Mathworks. 2007.

4. ADVANCED CONTINUOUS SIMULATION LANGUAGE (ACSL) User Guide/Reference Manual . AEgis Technologies. 2006.

5. SYSQUAKE User's Manual. Calerga Switzerland. 2007

6. J. J. Granda and F. E. Cellier, eds. "Proceedings of ICBGM'2005. 7h International Conference on Bond Graph Modeling and Simulation“ Simulation Series, Vol 37 Nr 1, SCS Publishing, ISBN: 1-56555-287-3 January 2005.

7. J. J. Granda and F. E. Cellier, eds. "Proceedings of ICBGM'2003. 6h International Conference on Bond Graph Modeling and Simulation“ simulation Series, Vol. 35, Nr 2, SCS Publishing, ISBN: 1-56555-257-1 January 2003.

8. J.J.Granda and G. Dauphin-Tanguy , eds. “Proceedings of ICBGM'2001, 5th International Conference on Bond Graph Modeling and Simulation". Simulation Series, Vol.33, Nr.1, SCS Publishing, ISBN: 1-56555-103-6. January 2001

9. Granda J.J. "ADVANCES IN SIMULATION" ASIM Vienna, Austria. Chapter of this book to be published by the Technical University of Vienna. The chapter is entitled: Granda J. "Advances in Software for Automation of The Modeling and Simulation Process Of Non-Linear Multienergy Systems Using MATLAB, SIMULINK, ACSL And CAMPG. February 2000

10. J.J.Granda and F.E.Cellier, eds. " Proceedings of ICBGM'99, 4th International Conference on Bond Graph Modeling and Simulation". Simulation Series, Vol.31, Nr.1, SCS Publishing, ISBN: 1-56555-155-9. Jan 1999

11. J.J.Granda and G. Dauphin-Tanguy , eds. “Proceedings of ICBGM'97, 3th International Conferen on Bond Graph Modeling and Simulation". Simulation Series, Vol.29, Nr.1, SCS Publishing, ISBN: 1-56555- 103-6. Jan 1997

12. F.E.Cellier and J.J. Granda, eds. “Proceedings of ICBGM'95, 2th International Conference on Bond Graph Modeling and Simulation". Simulation Series, Vol.27, Nr.1, SCS Publishing, ISBN: 1-56555-037-4. Jan 1995

13. J.J.Granda and F.E.Cellier, eds. “Proceedings of ICBGM'93, 1st International Conference on Bond Graph Modeling and Simulation". Simulation Series, Vol.25, Nr.1, SCS Publishing, ISBN: 1-56555- Jan 1993

14. Granda J. J. "Computer Aided Modeling Program (CAMP), a Bond Graph Preprocessor for Computer-Aided Design and Simulation of Physical Systems Using Digital Simulation Languages". Thesis. University of California, Davis December 1982

RESEARCH PAPERS:

15. Granda J. J. “S-Domain Bond Graph Models Computer Generated Transfer Functions for Electrical Circuits and Operational Amplifiers ”

Proceedings of the 2007 Internatinal Conference on Bond Graph Modeling and Simulation. San Diego. January 2007.

16. Nguyen L, Ramakrishnan J, Granda J, “International Space Station Centrifuge Rotor Models: A Comparison of the Euler-Lagrange and the Bond Graph Modeling Approach. Proceedings of the 2007 Internatinal Conference on Bond Graph Modeling and Simulation. San Diego. January 2007

17. Granda J. J., Ramakrishnan J., Louis H. Nguyen “Centrifuge Rotor Models A Comparison of the Euler-Lagrange and the Bond Graph Modeling Approach”. AIAA-Houston Annual Technical Symposium 2006 Gilruth Center May, 2006.

18. Granda J.J., Nguyen Louis “Alternative Techniques for Developing Dynamic Analysis Computer Models of the International Space Station, Space Shuttle and Orbiter Repair Maneuvers”. 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference. Newport, Rhode Island April 2006,

19. J. J. Granda , I. Sandoval, L Horta, “Morphing Structural Concepts Evaluation Criteria Using Dimensionless Analysis and Computer Simulation. 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference. Austin, Texas, April 2005

20. Elramady Alyaa, Granda J.J., “Modal Analysis of the Zvesda Mission of the Space Station With Bond Graphs” Proceedings of the 2005 Internatinal Conference on Bond Graph Modeling and Simulation. New Orleans, January 2005.

21. Granda J.J., “The CAMPG Symbolic Solution to Algebraic Loops in Bond Graph Models” Proceedings of the 2005 Internatinal Conference on Bond Graph Modeling and Simulation. New Orleans, January 2005.

22. Granda J, Montgomery R. “Automated Modeling And Simulation Using The Bond Graph Method For The Aerospace Industry“ Proceedings of

the 2003 AIAA Modeling and Simulation Technologies Conference 11-14 Austin, Texas August 2003

23. Montgomery R, Granda J. “Using Bond Graphs for Articulated, Flexible Multi-bodies, Sensors, Actuators, and Controllers with Application to the International Space Station”. Proceedings of the International Conference on Bond Graph Modeling and Simulation ICBGM 2003. Orlando, Florida, January 2003.

24. Granda J. “The CAMPG/MATLAB-SIMULINK Computer Generated Solution of Bond Graph Derivative Causality”. ”. Proceedings of the International Conference on Bond Graph Modeling and Simulation ICBGM 2003. Orlando, Fla. January 2003

25. Granda J. “The Role of Bond Graph Modeling and Simulation in Mechatronics Systems. An Integrated Software Tool: CAMPG, Matlab-Simulink**“** **Journal** of Mechatronics, Oxford England. November 2002.

26. Borutzky W, Granda J. "Bond graph based frequency domain sensitivity analysis of multidisciplinary systems". Journal of Systems and Control Engineering. July 2002.

27. Granda J, " Computer Generated Block Diagrams from Bond Graph Models CAMPG as a Tool Box for SIMULINK” Proceedings of the International Conference on Bond Graph Modeling and Simulation ICBGM'2001 Phoenix, Arizona. January 2001.

28. Piguet I, Granda J, Mocellin G, CAMPG/SYSQUAKE, an integrated Environment to Understand DynamicSystems and Design Controllers”. Proceedings of the International Conference on Bond Graph Modeling and Simulation ICBGM'2001 Phoenix, Arizona. January 2001

29. Borutsky W., Granda J. “Determining Sensitivities from and Incremental True Bond Graph”. Proceedings of the International Conference on Bond Graph Modeling and Simulation ICBGM'2001 Phoenix, Arizona. January 2001.

30. Morris M, Granda J. " Four Way Hydraulic Control Valve Design using Bond Graph Models, Computer Generated Block Diagrams and SIMULINK S Functions” Proceedings of the International Conference on Bond Graph Modeling and Simulation ICBGM'2001 Phoenix, Arizona. January 2001.

31. Granda J. " Methodes De Modelisation De Discontinuites De Systemes Nonlineaires Utilisant Des Modeles Generes Par Ordinateur, Des M-Functions Matlab Et Des S-Functions Simulink " (In French) July 2000. The English version is entitled. "Modeling Methods For Nonlinear Discontinuities Using Computer Generated Models, Matlab M-Functions And Simulink S-Funtions. Presented at. Conference International Francophone d’Automatique Ecole Centrale de Lille, France 5-8. July 2000

32. Granda J. “The Role of Bond Graph Modeling and Simulation in Mechatronics Systems. An Integrated Software Tool: CAMPG, Matlab-Simulink. Published in the Proceedings of MECHATRONICS 2000 Conference. Atlanta, Georgia. September 7, 2000.

33. Granda J. " Computer Generated Transfer Functions CAMPG: Interface to MATLAB and SIMULINK" Proceedings of the International Conference on Bond Graph Modeling and Simulation ICBGM'99. San Francisco, Ca. January 1999. Pg. 129

34. Granda J. "The Role of Physical System Modeling in Industry and Academia". Proceedings of the International Conference on Bond Graph Modeling and Simulation ICBGM'99. San Francisco, Ca. January 1999. Pg 7.

35. Fitsos P., Granda J. "Bond Graph Modeling of Engine Valve and Control System Using Electromechanical Rotary Actuators". Proceedings of the International Conference on Bond Graph Modeling and Simulation ICBGM'99. San Francisco, Ca. January 1999. Pg. 353

36. Granda J., Reus J. “New developments in Bond Graph Modeling Software Tools: The computer Aided Modeling Program CAMPG and MATLAB”. The IEEE International Conference on Systems, man, and Cybernetics. Orlando, Fla. October 1997.

37. Granda J. “Bond Graph Modeling Software Developments CAMPG Computer Aided Modeling Program New Features”. Proceedings of the International Conference on Bond Graph Modeling and Simulation ICBGM’97. Phoenix, Arizona January 1997. Pg. 31.

38. Granda J, Channell G “V-8 Internal Combustion Engine Bond Graph Model, a Detailed Modeling Procedure". Proceedings of the International Conference on Bond Graph Modeling and Simulation ICBGM’97. Phoenix Arizona. January 1997 Pg. 233.

39. H. A Mergen, Granda J., “Bond Graph Models and Finite Element Models for Engine Valve Spring Transient Response”. Proceedings of the International Conference on Bond Graph Modeling and Simulation ICBGM’97. Phoenix Arizona. January 1997 Pg. 129.

40. Granda J. J. “Advances in Modeling and Simulation of Dynamic Multiphysics Systems: New Challenges" Proceedings of the International Conference on Bond Graph Modeling and Simulation ICBGM’97. Phoenix Arizona. January 1997 Pg. 9.

41. Granda J. J., Reus J. "Three-dimensional Bond Graph Models Using CAMPG". Proceedings of the International Conference on Bond Graph Modeling and Simulation ICBGM'95. Las Vegas, NV. January 1995.

42. Granda J. J. " The future and Role of Bond Graphs in Industry ". Proceedings of the International Conference on Bond Graph Modeling and Simulation ICBGM'95. Las Vegas, Nv. January 1995.

43. Granda J. J., Dauphin-Tanguy G., Rombaut C. "Power Electronics Converter Electrical Machine Assembly Bond Graph Models simulated

with CAMP-ACSL". IEEE International Conference. Letouquet, France. October 1993.

44. Granda J. J. "Computer Aided Modeling of Multiport Element and Large Bond Graph Models with CAMPG". International Conference on Bond Graph Modeling and Simulation. ICBGM'93. San Diego, Ca. January 1993.

45. Granda J.J., Kong N. "Time Dependent Computational Relations between Finite Elements and Bond Graph Modeling". International Conference on Bond Graph Modeling and Simulation. ICBGM'93. San Diego, Ca. January 1993.

46. Granda J.J., Kong N. "Pseudo Bond Graph Models and Finite Element Models of Transient Heat Transfer Problems". International Conference on Bond Graph Modeling and Simulation. ICBGM'93. San Diego, Ca. January 1993.

47. Granda J.J., "Methodology of Bond Graph Modeling and Simulation with Computer Graphics for Undergraduate and Graduate Students." Multiconference on Engineering Education". San Diego. January 1990.

48. Granda J.J., Barlow M. “Three Dimensional Transient Heat Transfer Analysis Using Finite Elements and Computer Graphics". CADDAM Conference October 1989.

49. Granda J.J., Tang S. "Computer Simulation of Heat Transfer Models using a Pseudo Bond Graph Network". TRANSACTIONS Journal of the Society for Computer Simulation. September 1989.

50. Granda J.J., Lee K. "Computer Simulation of Mechanical Manipulators with model reference adaptive controllers." Proceedings of the Southeastern Simulation Conference. Hunstville, Alabama. October 1987.

51. Granda J.J., Sime K. "Computer Aided Modeling of the Four Stroke Internal Combustion Engine". Proceedings of the 30th Heat Transfer and

Fluid Mechanics Institute. California State University, Sacramento. June 1987.

52. Granda J.J., Ferner E. "Computer Simulation of a Hydraulic Four Way Control Valve." TRANSACTIONS Journal of the Society for Computer Simulation. January 1987.

53. Granda J.J. "Analysis of an Aircraft Landing Mechanism Using Computer Graphics and an Automatic Model Generator". Proceedings of the Summer Computer Simulation Conference. Reno, Nevada. July 28-30, 1986.

54. Granda J.J. "Modeling and Simulation of Electromechanical Systems using Computer Graphics". Proceedings of the Conference on Computer Graphics. California State University, Sacramento, Ca. March 1986.

55. Granda J. J., Ferner E, "Computer-Aided Simulation of a Hydraulic Four Way Valve". Proceedings of the Multiconference on Languages for Continuous Systems Simulation. San Diego, Ca. January 1986.

56. Granda J.J. "Computer Simulation of a Hydraulic Power Steering System with Mechanical Feedback". Proceedings of the 29th Heat Transfer and Fluid Mechanics Institute. CSU, Sacramento. Sacramento, Ca. June 1985.

57. Granda J.J. "Computer-Aided Control System Design using Bond Graph Modeling" Abstract Proceedings of the IEEE Control Systems Society 2nd Symposium on Computer-Aided Control System Design (CACSD). Santa Barbara, California. March 1985.

58. Granda J.J. "Computer Graphics Techniques for the Generation and Analysis of Physical System Models." Proceedings of the Multiconference on Artificial Intelligence, Graphics, and Simulation. San Diego, Ca. January 1985.

59. Granda J. J. "Computer Generation of Physical System Differential Equations using Bond Graphs." Journal of the Franklin Institute, January/February Issue, 1985

60. Granda J. "Computer Aided Design of Dynamic Systems." Proceedings of the Summer Computer Simulation Conference Boston, Mass. July 23-25. 1984.

61. Granda J. "Modeling and Simulation in a Computer Aided Design Curriculum." Annual Meeting of the American Society for Engineering Education. University of Utah. June 24-28, 1984

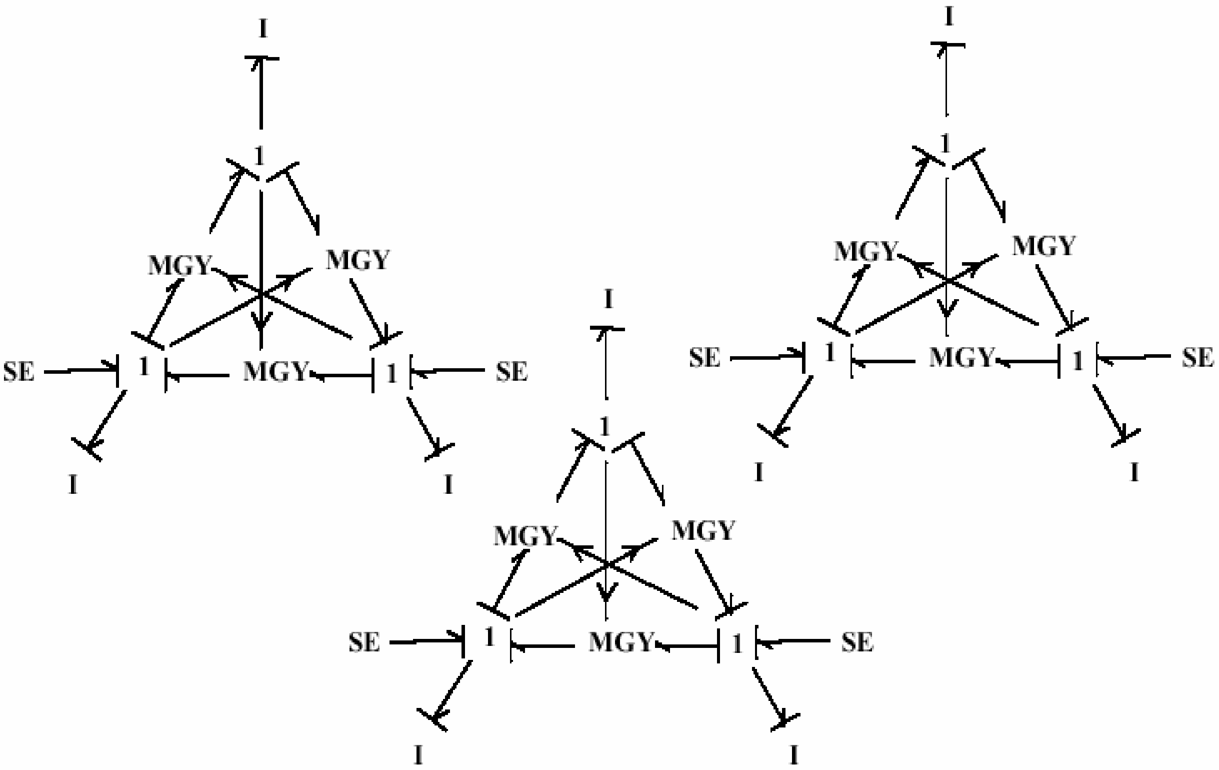
62. Granda J. "Bond Graph Modeling Solutions of Algebraic Loops and Differential Causality in Mechanical and Electrical Systems." Proceedings of the Tenth International Association of Science and Technology for Development- IASTED. International Conference. Applied Simulation and Modeling ASM'84. San FranciscoJune 4-6, 1984.

63. Granda J. J. "Computer Generation of Mechanical Systems Differential Equations" NATO/ National Science Foundation Advanced Study Institute on Computer-Aided Analysis and Optimization of Mechanical System Dynamics. The University of Iowa, August 1983.

64. Granda J. J. "A guide to Using the Computer Aided Modeling Program." Department of Mechanical Engineering, California State University, Sacramento. June 1983

CAMPG

The Universal Bond Graph Modeling Preprocessor for Dynamic and Mechatronics Systems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